(57) PARTIAL INTERACTION MECHANISM OF HEADED STUD EMBEDDED IN CONCRETE UNDER PULLOUT FORCE

Soty ROS[1] and Hiroshi SHIMA[2]

[1] PhD, Department of Infrastructure System Engineering
Kochi University of Technology
Kochi, Japan
e-mail: 136004m@gs.kochi-tech.ac.jp

[2] Professor, Department of Infrastructure System Engineering
Kochi University of Technology
Kochi, Japan
e-mail: shima.hiroshi@kochi-tech.ac.jp

This study aims to develop a complete design model of shear force-slip relationship of headed stud with the presence of external normal force. By means of concrete wedge model, the partial interaction mechanisms of headed stud were demonstrated to be represented by axial force-head displacement relationship, and shear force carried by stud shank-lateral slip relationship. Partially, this paper presents the first part of the model and proposes new design equations of the ultimate pullout capacity, and the axial force-head displacement relationship of single stud subjected to a combined shear and external normal force. It was found that the axial force-head displacement relationship could be represented by a unique enveloped curve by normalizing axial forces by the ultimate axial force and the head displacements by the diameter of the stud shank. The ultimate stud head displacements were found to vary from 0.13 to 0.15 times stud shank diameter.

Key words: *Headed stud; shear force-slip relationship, axial force; head displacement; wedge model.*

1. INTRODUCTION

Headed studs have been widely used as shear connectors in steel-concrete composite structures to transfer forces between the steel to concrete materials. In some conditions of the composite constructions, headed studs connectors transfer not only shear force but also a combined shear and tensile force such as infill walls, coupling beams, connections to composite column, or composite column bases[1)]. Accordingly, many investigations have been conducted and the design equations for shear capacity[1-12)], pullout capacity[13-21)] and the shear-tension interaction[3),4),5),22)23),24),25)] of headed studs have been proposed. Several studies were also extensively conducted on other types of shear connectors which have been used in the steel-concrete composite structures such as Pinned connector[26)], J-hook connector[27)], Perfobond shear connector[28)], and L-shape shear connector[29)]. In more rational design of composite structures not only the shear capacity, but also the shear force-slip relationships of the shear connector are required. Meanwhile, how partial interaction mechanism of headed stud under pullout force is important for shear force-slip relationships of headed stud under combined shear and normal force are demonstrated in the following subchapters.

(1) Shear force-slip relationship

a) Ultimate shear capacity

In terms of shear capacity of headed stud, the existing design equations given by different design codes[2),3),4),5),6)] are listed in **Table 1**. It was recommended that the shear capacity of headed stud is the smallest between V_{u1} (concrete failure) and V_{u2} (steel failure). Meanwhile, the equations to predict V_{u1} expressed in **Table 1** were developed by means of the experimental results of the comment push-out test method. On the other hand, based on an experimental study of Shima[30)], the shear capacity of headed stud was found to be significantly affected by the test method. He reported that there existed a normal compressive force ($-C_e$) which developed and acted upon the studs in the comment push-out test method and resulted in an increase of ultimate

Table 1. Existing equations for shear capacity of headed stud.

Sources	Units:	Concrete failure V_{u1}	Steel failure V_{u2}
JSCE[4),5)]	N and mm	$31A_s(h_{ss}/\phi)^{0.5}(f_c')^{0.5} + 10000$	$\chi A_s f_{su}$
PCI 6th[3)]	kips and inches	$317.9\lambda(f_c')^{0.5}\phi^{1.5}(h_{ef})^{0.5}$	
ACI 318-08[2)]	kips and inches	$k_{cp}40\lambda(f_c')^{0.5}(h_{ef})^{1.5}$	
Eurocode 4[6)]	N and mm	$0.29\phi^2(f_c'E_{cm})^{0.5}/\gamma_v$	
Note: V_u is the ultimate shear capacity, f_c' is the concrete compressive strength, E_{cm} is the concrete elastic modulus, ϕ is the stud shank diameter, h_{ss} is the stud height including stud head, h_{ef} is the effect embedded depth excluding stud head, and k_{cp}, χ, λ, and γ_v are constant, A_s is the cross sectional area of stud shank (mm^2) and f_{su} is the tensile strength of stud (N/mm^2)			

Table 2. Existing equations shear force-slip relationship of headed stud.

Sources	Shear force-slip relationship	
Ollgaard et al.[10)]	$V = V_u((1\text{-exp}(-0.71\delta))^{2/5}$	for ϕ =19mm
Chuah et al.[11)]	$V = V_u((1\text{-exp}(-2.8))^{2/5}$	for ϕ =9.5mm
Shima and Watanabe[15)]	$V = V_u (1\text{-exp}(-\alpha'\delta/\phi)^{2/5}$ $\alpha' = 11.5(1.1(\gamma-1)^2+1)\times(f_c'/f_{co}')$	for ϕ =19 & 25mm
Note: V_u is the shear capacity of headed stud (kN), γ is equal to V_{u1}/V_{u2}[15], δ is the slip (mm), and f_{co}' is equal to 30 N/mm^2.		

shear capacity of the stud. However, the exact value of ($-C_e$) in the comment push-out test remained unidentified. Similarly, the literature[9)] also found that the ultimate shear capacity of headed stud significantly increased when ($-C_e$) increased. In contrast, it significantly decreased due to the increase of the external normal tensile force ($+C_e$)[8)]. About 20% of shear capacity of headed stud was reduced because of the presence of $+C_e$[19)]. Referring to AISC[21)], a reduction of shear strength approximately 25% may be adequate for the anchors subjected to combined shear and tension.

Since the external normal force C_e has a significant influence on headed stud shear capacity, some interaction curves to predict the associated limit states has been developed and proposed[4),5),6),7),2),3),21)]. An elliptical interaction curve with 5/3 and 2 of exponents on both shear and tensile strength terms has been proposed by McMakin et al.[22)] and by the JSCE research committee on steel-concrete hybrid structures[4),5)], respectively. Similar elliptical interaction curve was also given by Guillet[23)]. However, the existing design codes such as ACI 318-08[2)], PCI 6th[3)], JSCE[4),5)], and EURO code[6),7)] and the existing research results failed to give a design model for headed stud shear capacity with different levels of C_e which could be in compression ($-C_e$) or in tension ($+C_e$).

(b) Shear force-slip relationship

Regarding to the shear force-slip relationship of headed studs, the existing design equations proposed by previous researchers are listed in **Table 2.** The most recent equation was developed by Shima and Watanabe[12)]. They found that the relationship between shear force and slip of headed studs could be represented by a unique enveloped curve by normalizing the shear forces by the ultimate shear force and the slips by stud shank diameter[12)]. Meanwhile, the ultimate slip was found to be approximately 0.3 to 0.4 times the stud shank diameter. These equations were also introduced by JSCE[4),5)]. However, the existing design equations fail to predict the shear force-slip relationship with the presence of C_e.

Therefore, this study aims to develop and propose a complete design model for shear capacity as well as the shear force-slip relationship of headed stud by taking into account the effect different levels of C_e. Partially, in this paper presents one third of the model in which the complete design equations for ultimate axial force C_u as well as the axial force C_s-head displacement δ_h (C_s–δ_h) relationship of single and double studs subjected to a direct pullout force or a combined shear and C_e were developed and proposed.

(2) Concrete Wedge Model

According to Shima[30)], different behaviors of headed stud affected by different test method can be explained by a concept of concrete wedge model as illustrated in **Fig.1**. Based on this concept, the shear resistance mechanisms of headed stud can be explained as shown in **Figs.2** and **3**. The total shear force carried by headed stud could be expressed as follows:

$$V = V_w + V_c \tag{3}$$

where V is the total shear force carried by headed stud (kN), V_w is shear force carried by concrete wedge (kN), and V_c is the shear resistance at the

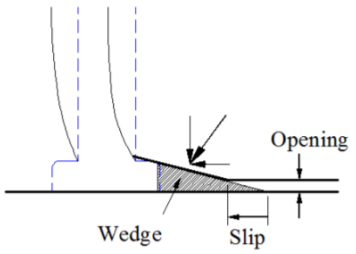
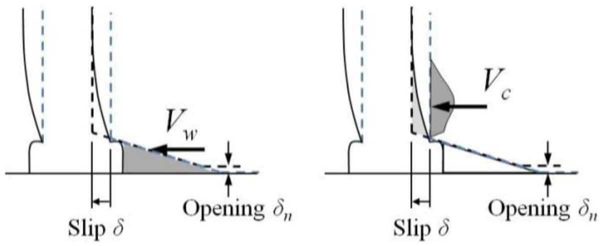
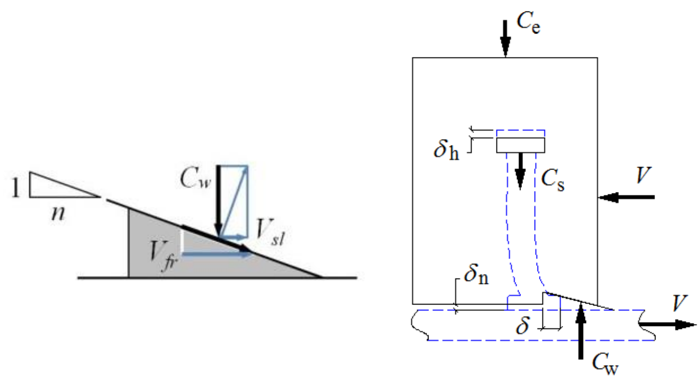


Fig.1. Concept of concrete wedge assumed by Shima[30].



(a) Concrete Wedge (b) Concrete crushing

Fig.2. Shear resistance mechanisms of headed stud.



(a) Concrete wedge (b) Normal force

Fig.3. Wedge model for headed by stud.

front face of headed stud (kN).

As shown in **Fig.3a**, on the surface of concrete wedge, V_w can be expressed as follows:

$$V_w = V_{sl} + V_{fr} \tag{4a}$$

$$V_{sl} = C_w/n \tag{4b}$$

$$V_{fr} = \mu C_w \tag{4c}$$

By replacing Eqs.4b and 4c into Eq.4a, the expression of V_w can be obtained as follows:

$$V_w = (1/n + \mu)C_w \tag{5}$$

As illustrated in **Fig.3b**, the expression of C_w can be given as follows:

$$C_w = C_e + C_s \tag{6}$$

Therefore, Eq.5 can be modified as follows:

$$V_w = (1/n + \mu)(C_e + C_s) \tag{7}$$

where C_e is the external normal force (kN), and C_s is the axial force carried by stud shank (kN).

By substituting Eq.7 into Eq.3, Eq.8 was obtained and it can be expressed as follows:

$$V = (1/n + \mu)(C_e + C_s) + V_c \tag{8}$$

It can be observed in Eq.8 that the equation to predict the shear capacity of headed stud with the presence of C_e will be completed if the unknown coefficients $1/n$ and μ, and the expressions of C_s and V_c are identified. Meanwhile, as illustrated in **Fig.3b**, the partial interaction mechanisms of headed stud with the presence of C_e could represented by the combination between the relationship between the axial force C_s and the head displacement δ_h, and that between V and δ.

2. PULLOUT FORCE/AXIAL FORCE OF HEADED STUD C_s

The development of C_s as well as the relationship between C_s and δ_h of single stud under direct pullout force, and combined shear and external normal force were examined by two experimental conditions. These experimental conditions were examined by means of the existing research results found by other researchers[14),15),20),24),25)].

(1) Experimental conditions for single stud

The properties of all tested specimens and the illustration of the experimental setups are respectively presented in **Table 3** and **Fig.4**. The names of all specimens were given as S-shank diameter-effective height-concrete strength (S-ϕ-h_{ef}-f_c':S-12-65-35). The single headed stud embedded in concrete and loaded in tension was shown in **Fig.4a** and **b**. During the test, the axial force C_s and the vertical opening δ_n representing the vertical relative slip between stud and concrete were measured and recorded until failure.

Two different experimental conditions were also conducted as shown in **Fig.4c**. The specimen S-13-70-23 was simultaneously subjected to both shear and axial force while S-13-70-23* was subjected to only pullout force. The loading histories of S-13-70-23 are given in **Fig.5**.

(2) Ultimate Pullout Force/Axial force C_u of Single Stud

The existing design equations to predict C_u of headed stud embedded in concrete are given in **Table 4**. These formulas were proposed in cased of cone shape concrete breakout at ultimate and no cracking as well as edge effect was taken into account. Some formulas were developed based on a model of concrete cone breakout with 45^o of inclination as illustrated in **Fig.6a**. Meanwhile, the idealized concrete cone with 35^o of inclination as shown in **Fig.6b** was also utilized[2),13)]. In terms of the existing experimental results of the literatures [14),15),20),24),25)], failures of specimens were governed by breaking out of concrete with an appearance of concrete cone similarly to the illustration in Fig.8a while the values of $C_{u.exp}$ were listed in **Table 5**.

The comparison between the experimental results of the literatures the calculation results by means of the equations given in **Table 4** are shown in **Table 5**. It can be observed that the equation proposed by Bode and Roik[16)] and ACI[17),18)] could conservatively predict the ultimate pullout capacity of headed stud with 22%, 11%, and 32% of underestimation in average, respectively.

Table 3. Detail of tested specimens.

Specimens	Stud height h_{ss} (mm)	Stud diameter ϕ (mm)	Effective height h_{ef} (mm)	f_c' (N/mm^2)	E (kN/mm^2)	Loading condition
S-12-65-35, (4a)	75	12	65	33	200	Pullout
S-16-90-35, (4a)	100	16	90	33	200	Pullout
S-8-50-45.6, (4b)	55	8	50	45.6	200	Pullout
S-8-50-31.2, (4b)	55	8	50	31.2	200	Pullout
S-13-70-23, (4c)	80	13	70	23	245	Pull-Shear
S-13-70-23*, (4c)	80	13	70	23	245	Pullout

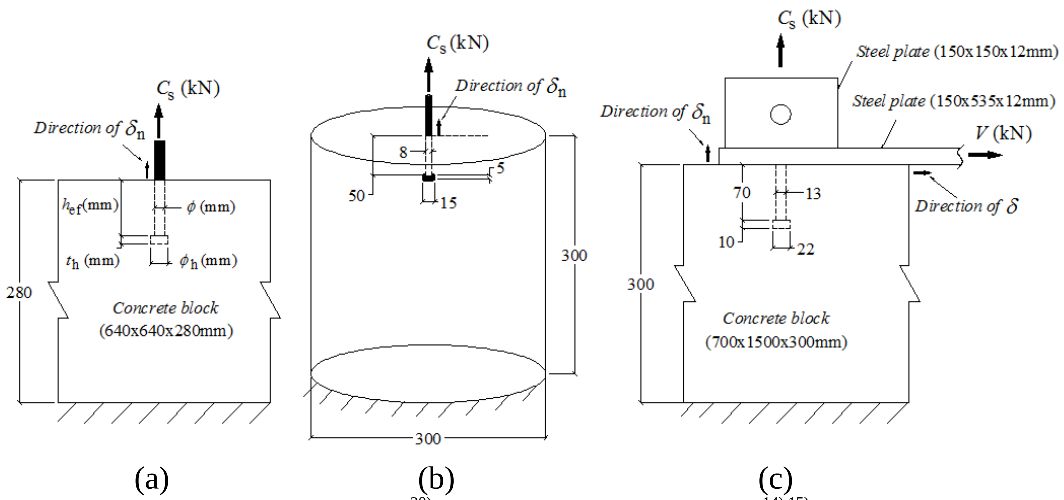


Fig.4. Experimental condition: (a) static pullout test[20)], (b) three dimensional pullout test[14),15)], and (c) shear and pullout test[24),25)].

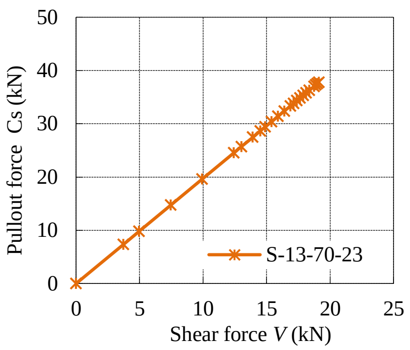


Fig.5. Loading history of the tested specimens S-13-70-23 of [24-25].

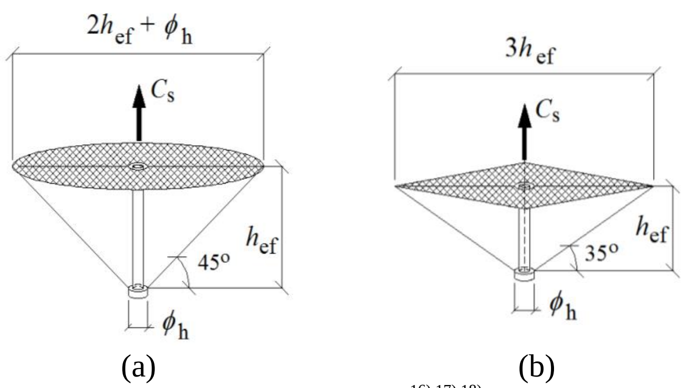


Fig. 6. (a) Concrete breakout bodies idealized[16),17),18)], (b), Idealized concrete cone for individual fastening under tensile loading after CCD method[2),13)].

However, the formula proposed by ACI 318-08[2] and CCD[13] gave about 16% of overestimation in average. Similar indication was also given by Pallares and Hajjar[1] after they examined the experimental C_u of 163 headed studs under pullout force. They found that the average ratio between tested and predicted results by means of the equation given by ACI 318-08[2] and CCD[13] was approximately 0.885.

Even though the existing formulas listed in **Table 4** were already proposed and commonly used to predict the ultimate axial force of headed stud C_u, a more accurate formula for C_u is concerned in this study. It has been observed that the predicted results by means of the equation given by ACI 318-05[17] gave more accuracy than others. However, based on the existing typical experimental results[14),15),20),24),25)], the constant value of 12.8 should be modified. As shown in **Table 6**, when the tested $C_{u.exp}$ were divided by the expression of $(h_{ef})^{1.5}\times(f_c')^{0.5}$, the average ratio was found approximately 14. This division was made based on the reports in the literatures stating that the ultimate pullout force of headed stud in concrete is proportional to the square root of concrete compressive strength as well as 1.5 power the effective embedded length[2),13),26),17)].

Therefore, the following formula was proposed by the authors to precisely predict the ultimate pullout force of single headed stud embedded in concrete.

$$C_u = 14 \times (h_{ef})^{1.5} \times \sqrt{f_c'} \qquad (14)$$

where C_u is the ultimate pullout/axial force of single stud (N), h_{ef} is the effect embedded depth (mm), and f_c' is the concrete compressive strength (N/mm^2).

It can be seen in Table 7 that Eq.14 can precisely predict C_u of headed stud with $C_{u.exp}$ to $C_{u.Eq.(14)}$ ratio varied from 0.97 to 1.06.

(3) Axial Force-Head Displacement C_s-δ_n Relationship of Single Stud

Based on the experimental results of the literatures[14),15),20),24),25)], only the relationships between C_s and opening displacement of stud δ_n were obtained as plotted in **Figs.7a**, **b**, and **c**. It can be understood that the pullout capacity of headed stud depends on the embedded length as well as the strength of concrete. As shown in **Fig.7a**, with the

Table 4. Existing design equations for pullout capacity of headed stud.

Literatures	Design Equations	Unit
Bode and Roik[16]; $C_{u.1}$ (kN)	$C_{u.1} = 8.9\times(h_{ef})^{0.5}\times(h_{ef}+\phi_h)\times(f_{cc}')^{0.5}$	(kN)
Concrete Capacity Design (CCD)[13]; C_{u2}(kN) And ACI 318-08[2]	$C_{u.2} = 15.5\times(h_{ef})^{1.5}\times(f_{cc}')^{0.5}$	(kN)
ACI 349-97[18]; $C_{u.3}$ (kN)	$C_{u.3} = 0.96\times h_{ef}\times(h_{ef}+\phi_h)\times(f_{cc}')^{0.5}$	(kN)
ACI 318-05[17] ; $C_{u.4}$ (kN)	$C_{u.4} = 12.8\times(h_{ef})^{1.5}\times(f_c')^{0.5}$	(kN)
Note: f_{cc}' = 1.18 f_c' of ACI 349-97[18]; (f_{cc}': compressive strength measured in cube with length of 200mm)		

Table 5. Experimental results and calculation results.

Specimens	$C_{u.exp}$ (kN)	$C_{u.1}$ (kN)	$C_{u.exp}/C_{u.1}$	$C_{u.2}$ (kN)	$C_{u.exp}/C_{u.2}$	$C_{u.3}$ (kN)	$C_{u.exp}/C_{u.3}$	$C_{u.4}$ (kN)	$C_{u.exp}/C_{u.4}$
S-12-65-35	43	35.00	1.23	50.69	0.85	33.06	1.30	38.53	1.12
S-16-90-35	72.5	56.02	1.29	82.58	0.88	62.27	1.16	62.78	1.15
S-8-50-45.6	32	27.62	1.16	40.20	0.80	22.89	1.40	30.56	1.05
S-8-50-31.2	29	22.85	1.27	33.25	0.87	18.93	1.53	25.28	1.15
S-13-70-23	38	32.85	1.16	47.29	0.80	32.21	1.18	35.95	1.06
S-13-70-23*	38	32.85	1.16	47.29	0.80	32.21	1.18	35.95	1.06
Average Ratio			1.22		0.84		1.32		1.11

Table 6. Detail of tested specimens.

Specimens	Effective height h_{ef}(mm)	f_c' (N/mm^2)	$C_{u.exp}$ (kN)	$C_{u.exp}/((h_{ef})^{1.5}\times(f_c')^{0.5})$	$C_{u.Eq.(14)}$ (kN)	$C_{u.exp}/C_{u.Eq.(14)}$	$\delta_{h.u}$ (mm)	$\delta_{h.u}/\phi$
S-12-65-35, (4a)	65	33	43	14.28	43.40	1.02	1.63	0.136
S-16-90-35, (4a)	90	33	72.5	14.78	70.72	1.06	2.11	0.132
S-8-50-45.6, (4b)	50	45.6	32	13.40	33.42	0.96	1.10	0.137
S-8-50-31.2, (4b)	50	31.2	29	14.68	27.65	1.05	1.10	0.137
S-13-70-23, (4c)	70	23	38	13.53	39.32	0.97	2.01	1.150
S-13-70-23*, (4c)	70	23	38	13.53	39.32	0.97	2.01	1.150
Average				14.02		1.01		

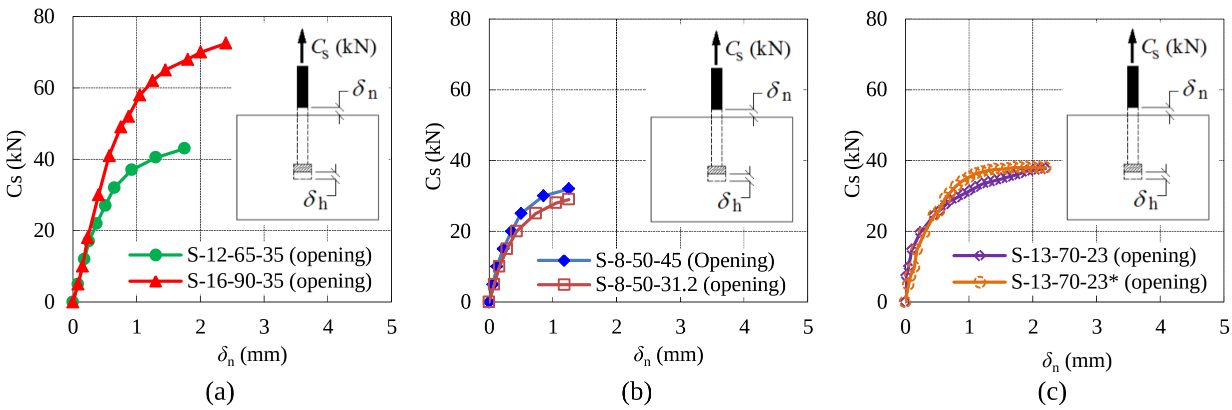


Fig.7. C_s-δ_n relationship: (a) [20], (b) [14,15], and (c) [24,25].

same concrete strength, the longer embedded length specimen gave higher axial force at breaking out of concrete or ultimate pullout capacity. Meanwhile, **Fig.7b** suggested that with the same embedded length, the higher concrete strength specimen gave higher pullout capacity. In case of identical specimens, as shown in **Fig.7c**, similar curves of C_s-δ_n relationship were obtained despite different loading histories.

It is generally accepted that when the stud embedded in concrete was subjected to pullout/axial force C_s, the stud shank elongated with Δ_e and the head of stud displaced with δ_h while the combination between Δ_e and δ_h was the opening displacement δ_n. Accordingly, the following equation can be expressed:

$$\delta_n = \Delta_e + \delta_h \qquad (15a)$$

Or

$$\delta_h = \delta_h - \Delta_e \qquad (15b)$$

where δ_n is the opening displacement (mm), Δ_e is the elongation of stud shank (mm), and δ_h is the head displacement (mm).

If the stud shank remains in elastic ranges until breaking out of concrete, stud shank elongation can be expressed as follow:

$$\Delta_e = \varepsilon_s \times h_{ef} \qquad (16)$$

where ε_s is the tensile strain in stud shank (μ), and h_{ef} is the effective embedded length (mm).

Based on the experimental results of Qian and Li[14),15)], Solomos and Berra[20)], and Ohtani et al.[24),25)], it was confirmed that no signs of yielding in the stud shanks since the tensile stresses in the shanks were far below the tensile yield strength of the studs. Therefore, the development of tensile strain in stud shank under axial force can be calculated from Eq.17.

$$\varepsilon_s = C_s/E_s A_s \qquad (17)$$

where ε_s is the tensile strain in stud shank (μ), C_s is the axial force(kN), E_s is the young's modulus of stud (kN/mm^2), and A_s is the cross sectional area of stud shank (mm^2).

By substituting Eq.17 into Eq.16, then Eq.16 into Eq.15b, the following equation can be obtained.

$$\delta_h = \delta_n - (h_{ef} \times C_s/E_s A_s) \qquad (18)$$

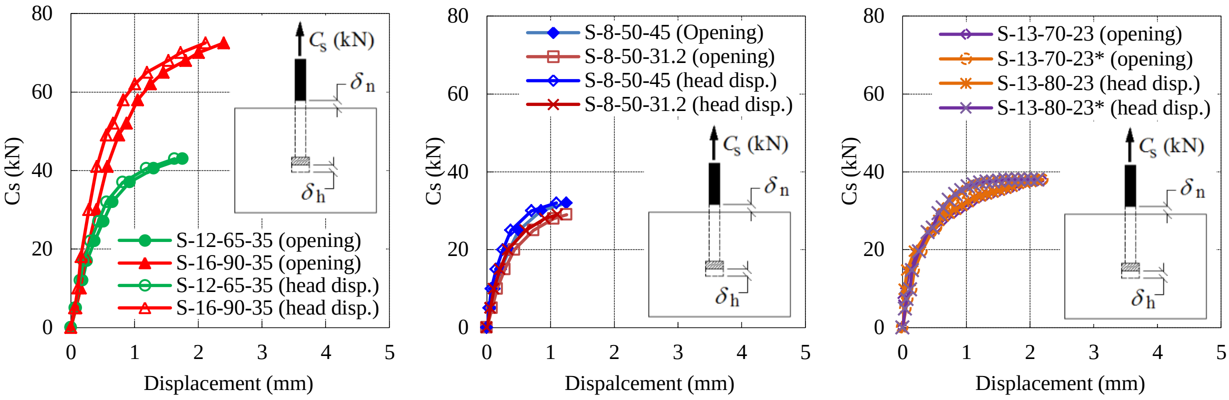
Accordingly, the developments δ_h could be calculated from the experimental results of Qian and Li[14),15)], Solomos and Berra[20)], and Ohtani et al.[24),25)]. The relationship between C_s and δ_h were obtained as plotted in **Figs.8** and 9. It can be observed in **Figs.8a**, **b**, and **c** that C_s-δ_h relationships were almost identical with C_s–δ_n relationships, especially when the embedded length was short. This would imply that bond between concrete and stud shank was negligible small.

Based on the experimental study of Shima and Watanabe[12)], the shear force-slip relationship of headed studs could be represented by a unique curve by normalizing shear force by the ultimate shear force and the slip with the stud shank diameter. Therefore, the same assessment was applied to C_s-δ_h relationships as shown in **Fig.10**. It can be seen that a unique enveloped curve also appeared when the normalization was applied regardless of the size of stud, the embedded length, and the strength of concrete. Therefore, it implied that the relationship between C_s and δ_h can be represented by a unique enveloped curve by normalizing C_s by C_u and δ_h by ϕ. Meanwhile, the curve was found to fit best with an exponential equation whose expression was given as follows:

$$C_s/C_u = (1 - e^{-28\times(\delta_h/\phi)})^{0.8} \qquad (19a)$$

$$C_u = 14 \times (h_{ef})^{1.5} \times \sqrt{f_c'} \qquad (19b)$$

Where C_u is the ultimate pullout force of a single stud (N), and ϕ is the diameter of stud shank (mm),



(a) (b) (c)

Fig.8. Developments of opening and head displacement of: (a) [20], (b) [14-15], and (c) [24-25].

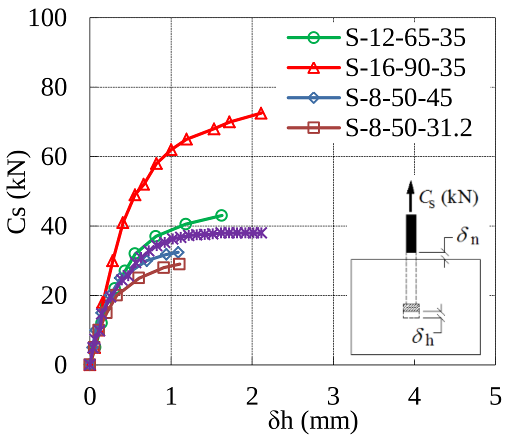


Fig.9. Axial force and head displacement relationship of: (a) [20], (b) [14-15], and (c) [24-25].

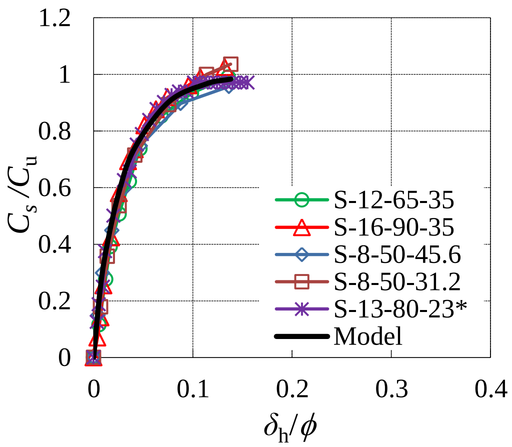


Fig.10. $C_s/C_u - \delta_h/\phi$ relationship of single headed studs under axial forces.

and f_c' is the concrete compressive strength (N/mm^2).

The experimental results of Qian and Li[14),15)], Solomos and Berra[20)], and Ohtani et al.[24),25)] suggested that the ultimate head displacement of single stud embedded in concrete and subjected to axial force was approximately between 0.13 to 0.15 times the diameter of stud shank regardless of the size of stud, the embedded length, and the strength of concrete.

However, in order to complete the design model for shear force-slip relationship of headed stud with the presence of C_e, more investigations are required to determine the coefficient $1/n$ and μ, and the expressions of V_c which are the next targets of this study.

3. CONCLUSIONS

The following conclusions can be derived from this study:

(1) Concrete wedge model was demonstrated to be suitable to be used to model the shear force and slip relationship with the presentence of the external normal force.

2. The equation to predict the ultimate pullout/axial force of single stud was modified and proposed as follows:

$$C_u = 14\times(h_{ef})^{1.5}\times(f_c')^{0.5}$$

4. The relationship between axial forces and head displacements of single stud under axial force or under combined shear and external normal force could be represented by a unique enveloped curve by normalizing the axial forces with the ultimate axial force and the head displacements by the diameter of the stud shank regardless of stud size and concrete strength.

5. The equation to predict the enveloped curve of the relationship between axial forces and head displacements of single stud was developed and proposed as follows:

$$C_s/C_u = (1-\exp(-28\times(\delta_h/\phi)))^{0.8}$$

Meanwhile, the ultimate head displacement of single and double studs was found approximately between 0.13 to 0.15 times the diameter of stud shank regardless of concrete strength and embedded length.

REFERENCES

1) Pallares, L. and Hajjar, J. F.: "Headed steel stud anchors in composite structure, Part I: Shear". *J Constr Steel Res*, Vol.66, pp.198-212, 2010.
2) American Concrete Institute Committee 318 (ACI).: "Building code requirements for structural concrete (ACI 318-08) and commentary (ACI 318R-08)". Farmington Hills (MI): American Concrete Institute; 2008.
3) Prestressed Concrete Institute (PCI).: "PCI design handbook". 6th ed. Chicago (IL): Precast/Prestressed Concrete Institute; 2004.
4) Japan Society of Civil Engineers: "Guideline for performance verification of steel-concrete hybrid structures", *Hybrid Structure Series 2*, JSCE, 2006.
5) Japan Society of Civil Engineers: "Standard specifications for hybrid structures". JSCE, 2009 (in Japanese).
6) Johnson, R. P., and Anderson, D., "Designers' Guide to EN 1994-1-1: Eurocode 4 : Design of Composite Steel and Concrete Structures, Part 1-1: General Rules and Rules for Buildings". Thomas Telford, 2004.
7) Johnson, R. P.: "Shear connection in beams that support composite slabs – BS5950 and EN 1994-1-1", *The Struct Eng*, Vol.83, No.22, pp.21-24, 2005.
8) Toyama, M. and Shita, H.: "Experimental study on bond characteristics depending on lateral tensile stress between steel plate with stud and concrete", *Con Res and Tech*, Vol.15, No.1, pp.1-12, 2004.
9) Kasai, Y., Kawamura, T., Oshita H.: "Experimental study on unified model of bond characteristic depending on lateral pressure between steel plate with stud and concrete". *Con Res and Tech*, Vol.13, No.2, pp.1-13, 2002.
10) Ollggaard, J. Slutter, R., Fisher, J.: "Shear strength of stud connector in light weight and normal-weight concrete". *AISC Eng J*, pp.55-64, 1971.
11) Chuah, C. L., Shima, H. and Virach, R.: "Strength and deformational behaviors of studs embedded in high strength prestressed concrete", *Proceeding of Japan Concrete Institute*, Vol.13, No.2, pp.1033-38, 1991.
12) Shima, H. and Watanabe, S.: "Formulation for Load-Slip Relationships of Headed Stud Connector", *Proceedings of the 34th IABSE Symposium*, September 22-24, 2010, Venice.
13) Fuchs, W., Eligehausen, R., Breen, J. E.: "Concrete capacity design approach for fastening to concrete", *ACI Struct J*, Vol.92, No.4, pp.73-94, 1995.
14) Qian, S. and Li, V. C.: "Influence of material tensile ductility on headed anchor pullout performance", *ACI Mat J*, Vol.106, No.1, pp.72-81, 2009.
15) Qian, S. and Li, V. C.: "Headed anchor/engineered cementitious composites (ECC) pullout behavior", *J of Advance Con Tech*, Vol.9, No.3, pp.339-351, 2011.
16) Bode, H. and Roik, K.: "Headed Studs-Embedded in Concrete and Loaded in Tension", *American Concrete Institute*, ACI Special Publication, SP 103, No.4, pp.61-88.
17) ACI Committee 318.: "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)". *American Concrete Institute*, Farmington Hills, MI, pp.430, 2005.
18) ACI Committee 349.: "Code requirements for nuclear safety related concrete structures and commentary", (ACI 349-97, ACI 349R-97), Appendix B, C, (1997 April, American Concrete Institute, Farmington Hills, Mich).
19) Mizuguchi, K., et al.: "An experimental study on shear strength characteristics of stud for precast PC floor slab-Inabe River Bridge", *Proceeding of JSCE 5th Annual Meeting*, pp.312-313, 1999.
20) Solomos, G. and Berra, M.: "Testing of anchorages in concrete under dynamic tensile loading". *Mat and Struct*, Vol.39, pp.695-706, 2006.
21) American Institute for Steel Construction (AISC).: "Seismic provisions for structural steel buildings", ANSI/AISC 341-05, AISC. Chicago (IL): American Institute for Steel Construction; 2005.
22) McMakin, P. J., Slutter, R. G. and Fisher, J. W.: "Headed steel anchor under combined loading", *Eng J AISC*, pp.43-52, 1973.
23) Guillet, T.: "Behavior of Metal Anchors under combined tension and shear cycling loads", *ACI Struct J*, Vol.108, No.3, pp.315-323, 2011.
24) Ohtani, Y., and Fukumoto, Y.: "Failure behavior of stud anchor due to pull-out tension", *Technology Reports of the Osaka University*, Vol.39, pp.297-305, 1989.
25) Ohtani, Y., Baba, S., Morito, Y. and Fukumoto, Y.: "Behavior of stud anchor subjected to combined loads". *J of Struct Eng, JSCE*, Vol.37A, pp.1387-1396, March 1991.
26) Psycharis, I. N. and Mouzakis, H. P.: "Shear resistance of pinned connectors of precast members to monotonic and cyclic loading", *Eng Struct*, Vol.41, pp.413-427, 2012.
27) Liew, J. Y. R. and Sohel, K. M. A.: "Lightweight steel-concrete-steel sandwich system with J-hook connectors", *Eng Struct*, Vol.31, No.5, pp.1166-1178, 2009.
28) Candido-Martins JPS., Costa-Neves LF. and Vellasco PCG da S.: "Experimental evaluation of the structural response of Perfobond shear connectors", *Eng Struct*, Vol.38, No.8, pp.1976-1985, 2010.
29) Soty R. and Shima H.: "Formulation for shear force-relative displacement relationship of L-shape shear connector in steel-concrete composite structures", *Eng Struct*, Vol.46, pp.581-592, 2013.
30) Shima H.: "Effect of test method on shear resisting mechanism of headed stud", *Journal of Structural Eng./Earthquake Eng., JSCE*, 2011; (Doboku Gakkai Ronbunshuu A1, 2011; Vol.67, No.2: 307-319. (In Japanese).

(Received September 09, 2013)