(11) DEFORMATION BEHAVIORS OF HEADED STUD UNDER SHEAR AND NORMAL FORCES

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Shear resisting mechanisms of headed stud under shear and normal forces were examined by means of a modified push-out test method. Shear force and slip relationships of headed stud under different levels of external normal force were observed. It was found that the ultimate shear force of headed stud increased when the external compressive normal force. The normal openings were found to have linear relationships with the lateral slips and an equation representing the relationships was developed and proposed as a function of the external normal force and the concrete strength. Moreover, the mechanical behaviors of the stud with the presence of external normal force were explained by the concrete wedge model in which the total shear force V were carried by concrete crushing V_c and by the concrete wedge V_w. Accordingly, a particular specimen of stud without head was tested with the aim of separating the shear force carried by concrete crushing V_c and that carried by the concrete wedge V_w. As a result, an equation of a unique enveloped curve of the relationship between V_c and slip was developed.

Key words: *Wedge model, headed stud, shear force, slip, normal force, opening.*

1. INTRODUCTION

Headed studs have been widely used as shear connectors in steel-concrete composite structures to transfer shear force from steel to concrete and vice versa. In more rational design, not only the shear capacity, but also the shear force-slip relationships of the shear connectors were examined. Accordingly, numerous of studies have been conducted for these purposes.

In 2009, Shima and Watanabe[1)] examined the shear force-slip relationship of the headed stud shear connector by means of push-out test method. The research results of Ollgaard et al.[2)] and Chuah et al.[3)] were also discussed in their study. As a result, Shima and Watanabe proposed an equation representing the enveloped curve of the shear-slip relationships of headed stud shear connector. Meanwhile, the ultimate slips were found to vary from 0.3 to 0.4 times the stud diameter. Then the equation again appeared in the Design Specifications for Hybrid Structures of JSCE 2009[4)].

Moreover, the formulas of the shear strength of headed stud shear connectors were proposed by several researchers. Most recently, the formulas were given by the Guidelines for Performance Verifications of Steel-Concrete Hybrid Structures of JSCE 2006[5)] and again by the Design Specifications for Hybrid Structures of JSCE 2009[4)]. However, it has been known that the shear connectors are subjected to not only the shear force but also the pull-out force. According to Mizuguchi et al.[6)], the shear capacity of headed stud shear connectors decreases by 20% due to the presence of the pull-out force.

The experimental study on headed stud with the presence of external normal compressive and tensile force was respectively conducted by Kasai et al.[7)] and Yoyama and Oshita[8)]. It was found that, the ultimate shear force of headed stud increased with the external normal compressive force[7] and it significantly decreased with the increase of external normal tensile force[8]. However, the model of how to take into account the external normal force in the design of shear capacity of headed stud has not yet been developed.

Fortunately, in 2011 wedge model was firstly introduced by Shima[9)] to mechanically explain shear resisting behavior of headed stud when the external normal forces exist. However, a complete design model for headed stud under normal stress restriction has not yet been identified. Accordingly, this partially presents the effects of external normal force on the shear force-slip relationship of headed stud and on the relationships between the normal opening and lateral slip.

2. EXPERIMENT

(1) Specimen and measurements

Modified push-out test specimens with different stud height h_{ss}, stud diameter $ø$, stud tensile strength f_{su}, and concrete strength f_c' were constructed and tested. The properties of all specimens are listed in **Table 1** and the illustrations of the specimens are given in **Fig.1**. The space between the two studs is five times of its diameter. Normal and high strength headed studs whose dimensions and illustrations are given in **Table 2** and **Fig.2**, respectively were used in this study.

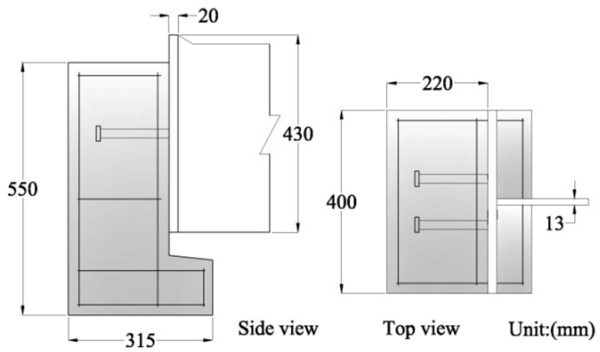


Fig.1. Detail of specimen.

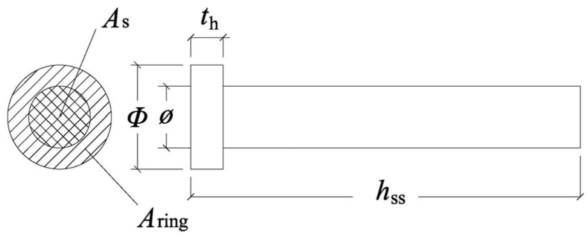


Fig.2. Detail of headed stud.

Table 2. Detail dimensions of headed stud used

Headed stud	Normal				High strength		
Diameter $ø$ (mm)	19			25	19		
Height h_{ss} (mm)	80	120	150	150	80	120	150
Head diameter Φ (mm)	32	32	32	40	32	32	32
Head thickness t_h (mm)	10	10	10	12	10	10	10
A_s (mm^2)	283			491	283		

During the test, the level of C_e can be easily controlled by the hydraulic jack. Different levels of C_e were applied on some typical specimens as listed in **Table 1**.

(2) Measurements

Displacement transducers were used to measure both lateral slip δ (mm) and normal opening δ_n (mm) between steel and concrete. The instruments were installed left-right and upper-lower symmetrically in pairs of all specimens as illustrated

Table 1. Properties of specimens

No.	Specimen name ($ø$-h_{ss}-f_{su}-f_c')	Stud diameter d_{ss} (mm)	Stud height h_{ss} (mm)	Stud tensile strength f_{su} (N/mm^2)	Concrete Strength f_c' (N/mm^2)	External normal force C_e(kN) per stud
No.1	19-120-437-31.5	19	120	437	31.5	0,-25,-50,-75
No.2	25-150-449-33.3	25	150	449	33.3	0
No.3	19-120-437-45.1	19	120	437	45.1	0,-35,-70
No.4	19-120-437-47.4	19	120	437	47.4	0
No.5	19-80-463-40.5*	19	80	463	40.5	0,-35,-70
No.6	19-150-453-34.5	19	150	453	34.5	0,-25,-50,-75
No.7	19-120-623-34.3	19	120	623	34.3	0
No.8	19-120-623-23.5	19	120	623	23.5	0
No.9	19-120-623-46.9	19	120	623	46.9	0
No.10	19-80-623-40.7	19	80	623	40.7	0,+5,-35,-70
No.11	19-150-623-39.1	19	150	623	39.1	0,-35,-70
No.12	19-120-623-33.2	19	120	623	33.2	0
*Stud without head						

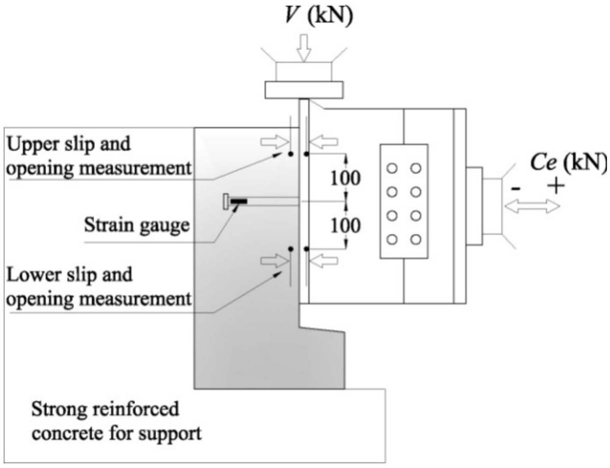


Fig.3. Test set-up.

in **Fig.3**. Meanwhile, stud strains were measured by strain gauges mounted on the left and right side of each stud close to its head. Additionally, the shear force V (kN) and the external normal force C_e (kN) were applied simultaneously by the hydraulic jacks while their magnitudes were measured by load cells.

3. WEDGE MODEL

As shown in **Fig.4**, after failure, the headed studs were pulled out and the concrete wedge was observed at the toe of the studs. This experimental result supported the proposed wedge model of Shima [9] which is illustrated in **Fig.5**.

In the concrete wedge model, the applied shear force V (kN) was carried by the concrete wedge V_w (kN) and by the concrete crush above the collar of the stud V_c (kN) as formulated in Eq.1.

$$V = V_w + V_c \tag{1}$$

Meanwhile, as shown in **Fig.6a**, V_w can be expressed as follows:

$$V_w = V_{sl} + V_{fr}$$

Since $V_{sl} = C_w/n$ and $V_{fr} = \mu C_w$

$$V_w = (1/n + \mu)C_w$$

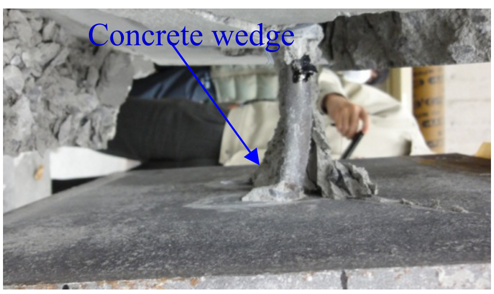
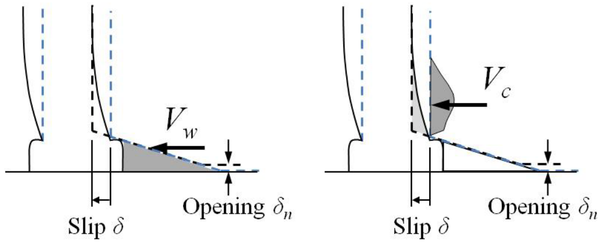
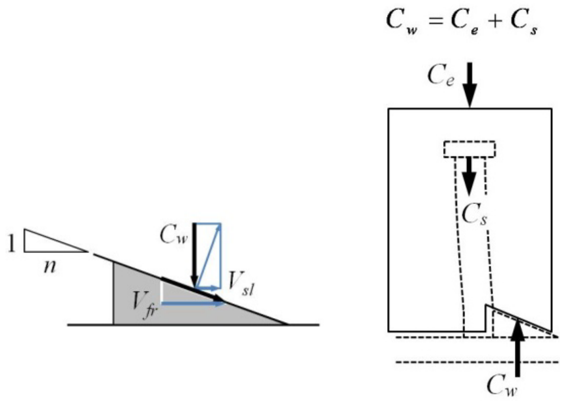


Fig.4. Concrete wedge in No.11(19-150-623-39.1).



(a) Concrete Wedge (b) Concrete crushing

Fig.5. Shear resistance mechanisms.



(a) Concrete wedge (c) Normal force

Fig.6. Wedge model for headed stud.

$$\text{Or } V_w = \mu_o C_w \tag{2}$$

where, $\mu_o = 1/n + \mu$. 1/n is the slope of wedge, and μ is the friction coefficient between concrete.

Moreover, as shown in **Fig.6b**, the normal force C_w (kN) depends on the external normal force C_e (kN) and the restricted force from stud head C_s (kN) as expressed in Eq.3.

$$C_w = C_e + C_s \tag{3}$$

$$\text{Or } C_w = C_e + A_s E_s \varepsilon_s \tag{4}$$

where,

A_s : Cross-sectional area of a stud (mm^2)

E_s : Young modulus of stud (kN/mm^2)

ε_s : Stud strain (μ)

Accordingly, the equation of the shear force on the stud Eq.1 can be expressed as follows:

$$V = \mu_o(C_e + A_s E_s \varepsilon_s) + V_c \tag{5}$$

Eq.5 represents the shear force of headed stud with the presence of external normal force. In this equation, the value of μ_o, a model of stud strain ε_s, and a model of V_c are the unknowns. Therefore, the aims of this research are to identify these unknown items and to propose a calculation model of V_c of headed stud with the presence of external normal force.

According to the shear resistance mechanisms of headed stud illustrated in **Fig.5**, the level of shear force carried by the wedge V_w and the concrete crush V_c are influence by the levels of the lateral slip δ and the normal opening δ_n. Therefore, the δ_n - δ relationships under different level of C_e are also required.

4. RESULTS AND DISCUSSION

(1) Shear force-slip relationships

Shear force-slip relationships of typical specimens upon which different levels of external normal forces were applied are given in **Fig.7a, Fig.7b**, and **Fig.7c**. It can be seen that the stiffness of headed studs increased when the external normal compressive force increased. As shown in **Fig.7c**, the peak of the curve increased with the external normal compressive force. This was due to the increase of shear force carried by the concrete wedge V_w when the normal force C_w increased. More importantly, these experimental results showed that the shear capacity of headed stud increased with the external normal compressive force. Similar results were also found by Kasai et al. (2002)[7] who examined the performance of headed studs with the presence of external normal compressive force varied from 0 kN to 50 kN by means of push-out test.

Furthermore, the external normal force also affected on the normal opening δ_n representing the level tensile stress in the stud. It implied that the relationship between tensile strain of stud ε_s and normal opening should be identified. Besides, the relationship between lateral slip δ and normal opening δ_n under different level of external normal force should be also identified.

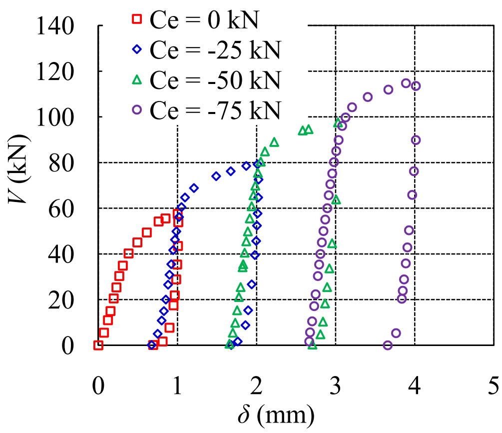


Fig.7a. V - δ relationship of No.1

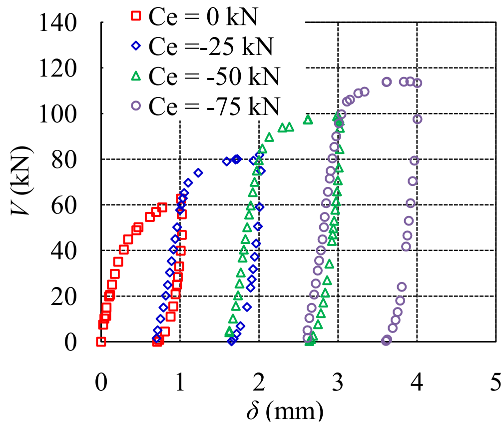


Fig.7b. V - δ relationship of No.6

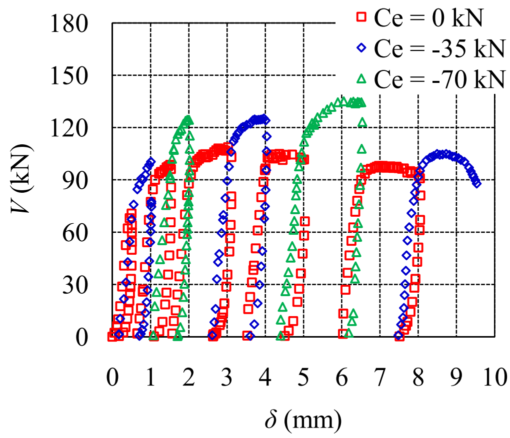


Fig.7c. V - δ relationship of No.11

(2) Opening and slip relationship

As shown in **Fig.8**, the relationships between the normal opening δ_n (mm) and the lateral slip δ (mm) were found to be linear. The slopes of the relationships decreased with the increase of the external normal compressive force. These results are reasonable that the values of normal opening decreased when the external normal compressive force increased. Accordingly, the relationships between δ_n/δ and C_e of all relevant specimens were examined. The experimental results showed a linear relationship between δ_n/δ and C_e of each specimen, **Fig.9a**, while, the value of δ_n/δ seemed to be effected by the concrete strength. Based on the experimental results, the relationship between δ_n/δ and C_e can be expressed as follows:

$$\frac{\delta_n}{\delta} = k_1 C_e + k_2 \tag{6}$$

where k_1 is a constant representing the average slope of the relationships, and k_2 is a constant at which the external normal force is zero. As listed in **Table 3**, the average value of k_1 was found to be 0.002 (k_1 = 0.002).

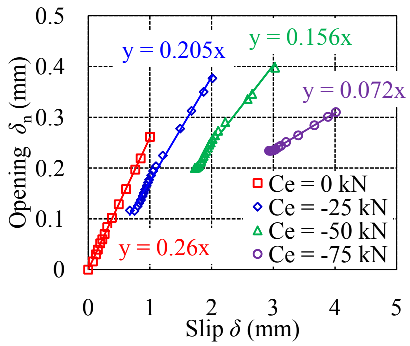


Fig.8a. δ_n - δ relationship of No.1. (19-120-437-31.5).

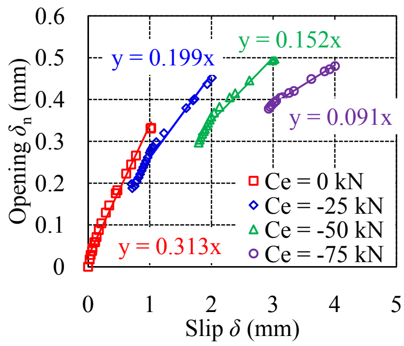


Fig.8b. δ_n - δ relationship of No.6 (19-150-453-34.5).

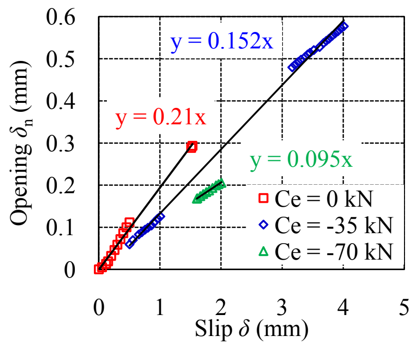


Fig.8c. δ_n - δ relationship of No.11 (19-150-623-39.1).

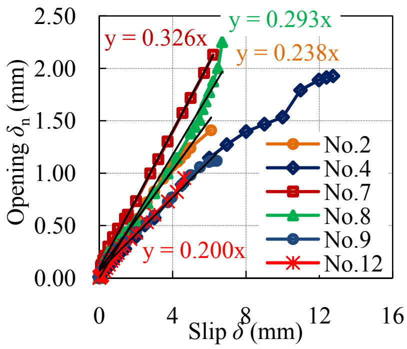


Fig.8d. δ_n - δ relationship of specimens with C_e = 0kN.

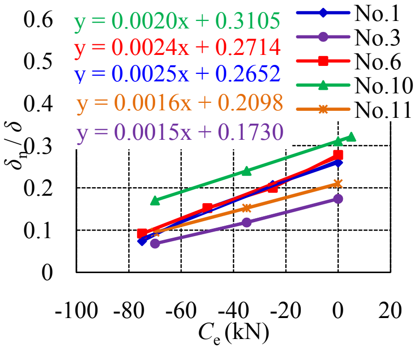


Fig.9a. δ_n/δ and C_e relationships.

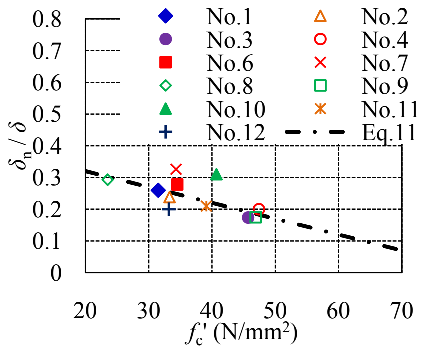


Fig.9b. δ_n/δ and f_c' relationships at C_e = 0 kN.

Table 3. Values of k_1 and k_2

No.	Specimen name ($ø$-h_{ss}-f_{su}-f_c')	k_1	k_2	External normal force C_e(kN) per stud
No.1	19-120-437-31.5	0.0025	0.2652	0,-25,-50,-75
No.2	25-150-449-33.3	-	0.2700	0
No.3	19-120-437-45.1	0.0015	0.1730	0,-35,-70
No.4	19-120-437-47.4	-	0.2000	0
No.6	19-150-453-34.5	0.0024	0.2714	0,-25,-50,-75
No.7	19-120-623-34.3	-	0.3400	0
No.8	19-120-623-23.5	-	0.2930	0
No.9	19-120-623-46.9	-	0.2000	0
No.10	19-80-623-40.7	0.0020	0.3105	0,+5,-35,-70
No.11	19-150-623-39.1	0.0016	0.2098	0,-35,-70
No.12	19-120-623-33.2	-	0.2000	0
Average value of k_1		0.0020		

As shown in **Fig.9b**, an equation of k_2 can be expressed as follows:

$$k_2 = 0.42 - \frac{f_c'}{200} \qquad (7)$$

Therefore, the relationship between the normal **Fig.7a** opening and the lateral slip is proposed as follows:

$$\frac{\delta_n}{\delta} = 0.002C_e + 0.42 - \frac{f_c'}{200} \qquad (8)$$

where,

δ_n : Normal opening (mm)
δ : Lateral slip (mm)
C_e : External normal force (kN)
f_c' : is the concrete compressive strength (N/mm^2).

By means of Eq.8, the normal opening δ_n can be calculated at any level of lateral slip δ and at any level of external normal force C_e. The value of δ_n at one level of δ represents the elongation of stud which is expressed by strain value ε_s. Additionally, as shown in Eq.9, an exact value of μ_o under different levels of C_e is required to calculate V_c from the total shear force V obtained from the experiment. Accordingly, the value of μ_o was examined by means of the experimental results of specimen No.5 in which the heads of studs were cut off to make strain in the studs $\varepsilon_s = 0$. It means that C_s was also equal to zero. The following subchapter presents the model of shear force carried by concrete crush V_c which can be directly calculated from the experimental results of specimen No.5.

(3) Relationship between V_c and δ

According to the concrete wedge model illustrated in **Fig. 5** and **Fig.6**, the external normal force C_e is carried by the concrete wedge; which means that the shear force carried by concrete crushing V_c is not effected by C_e or the curve of V_c and slip δ relationship of the stud under different levels of C_e is unique. Based on this hypothesis, the exact value of μ_o is the value that makes V_c - δ relationship curve become unique regardless of C_e. **Fig.10** and **Fig.11** give the V – δ and V_c – δ relationship of specimen No.5, respectively. As shown in **Fig.10**, the relationship between V_c and δ became unique when the value of μ_o was equal to 1.0 (μ_o = 1.0). From this value, if the slope of concrete wedge was assumed to be 1/5 ($1/n$ = 1/5), the friction coefficient μ was equal to 0.8 (μ = 1.0 – 1/5).

Additionally, by assuming the same area of stud body resisting against the V_c was equal to square of stud diameter $ø^2$, the stress σ = $V_c/ø^2$ is the same if the concrete strength is the same regardless of stud height and C_e. With μ_o = 1.0, the calculation of V_c was made for specimen No.10(19-80-623-40.7) and No.11(19-150-623-39.1) whose $V_c/ø^2$ - $\delta/ø$ relationships have to be the same as that of specimen No.5. Moreover, the strain values of specimen No.10 and No.11 were adjusted to make their $V_c/ø^2$- $\delta/ø$ relationships curves overlap with that of specimen No.5. As shown in **Fig.12**, a unique curve was obtained for the studs with the same diameter and concrete strength. This unique curve implied that at the same level of slip, the stress carried by concrete crushing was the same despite different level of external normal force. Additionally, the equations representing a unique curved of the $V_c/ø^2$ – $\delta/ø$ relationships can be given as follows:

$$\sigma = \sigma_{max}(1 - e^{-36\varepsilon})^{0.8} \ for\ (\varepsilon \le \varepsilon_o) \quad (10a)$$

$$\sigma = \sigma_{max} - 320(\varepsilon - \varepsilon_o) \ for\ (\varepsilon > \varepsilon_o) \quad (10b)$$

$$\sigma_{max} = 37.5\sqrt{f_c'} \quad (11)$$

where $\sigma = V_c/ø^2$ (N/mm²), $\varepsilon = \delta/ø$, ε_o is the value of $\delta/ø$ at the maximum stress σ_{max} , ε_o = 0.11, and δ is the slip (mm).

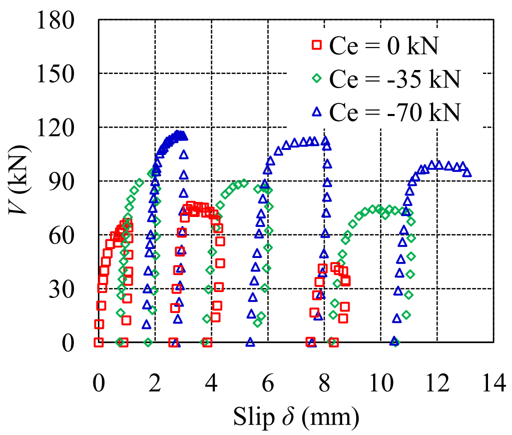


Fig.10. V - δ relationship of No.5.

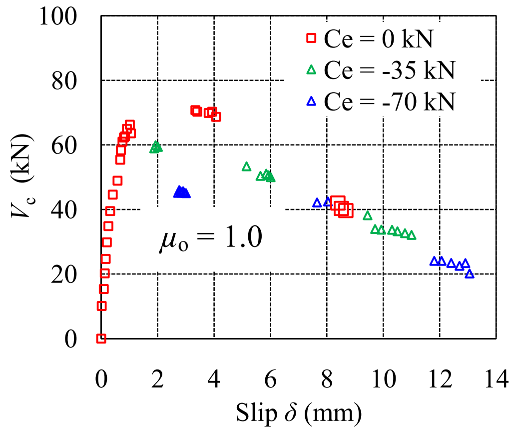


Fig.11. V_c - δ relationship of No.5.

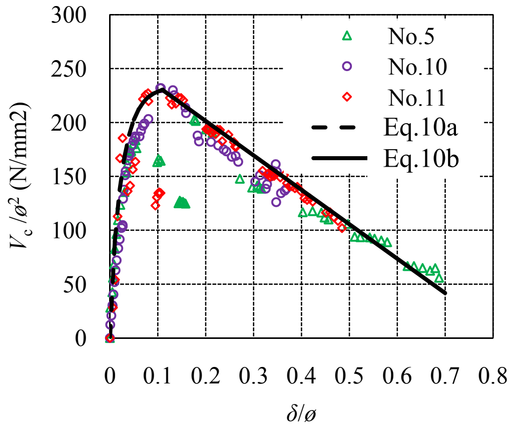


Fig.12. $V_c/ø^2$- $\delta/ø$ relationships No.5,10, 11.

4. CONCLUSIONS

The following conclusions can be derived from this study.

(1) The experimental results proved the occurrence of concrete wedge at the toe of the stud which would imply that the wedge model is applicable to be used to explain the shear resisting mechanisms of headed stud under shear and normal forces.

(2) Regardless of the external normal force and concrete strength, the relationships between the opening and the slip were found to be linear relationship whose equation was developed and proposed as follows:

$$\delta_n/\delta = 0.002Ce + 0.42 - f_c'/200$$

(3) A unique enveloped curve of $V_c/ø^2$ - $\delta/ø$ relationship of headed stud was observed at the coefficient of friction of 0.8 (μ = 0.8) regardless of external normal force. Accordingly an equation to predict the curve was established and proposed as follows:

$$\sigma = \sigma_{max}\left(1 - e^{-36\varepsilon^{0.8}}\right) \qquad \text{if } (\varepsilon < \varepsilon_o)$$
$$\sigma = \sigma_{max} - 320(\varepsilon - \varepsilon_o) \qquad \text{if } (\varepsilon > \varepsilon_o)$$
$$\sigma = V_c/\text{ø}^2$$
$$\sigma_{max} = 37.5\sqrt{f_c'}$$
$$\varepsilon = \delta/\text{ø}\ ;\ \varepsilon_o = 0.11$$

Meanwhile the maximum value of V_c was observed at ε_o of 0.11 or at the value of slip approximately 2.1mm.

However, further study should be conducted to imply the wedge model in the design of headed stud shear capacity with the presence of the external normal force.

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