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Formulation for Maximum Shear Force on L-Shape Shear Connector Subjected to Strut Compressive Force at Splitting Crack Occurrence in Steel-Concrete Composite Structures

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Abstract

This study investigates the performances of L-shape shear connectors subjected to strut compressive force in steel-concrete composite structures by means of beam type test method. Experimental data showed that splitting crack occurrence in the concrete in front of the shear connector controlled the maximum shear force on L-shape shear connector. An equation to predict the maximum shear force at splitting crack occurrence which is a function of width, height, thickness to height ratio of the shear connector, and the concrete strength is proposed. Moreover, the horizontal relative displacements of the head of the shear connector were found to have big increments with small increments of shear force after the occurrence of crack in the concrete from the head of the shear connector. Also, the occurrence of splitting crack in the concrete in front of the shear connector reversed the slip direction between concrete and steel plate in front of the shear connector.

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Keywords: L-shape shear connector, splitting crack, maximum shear force, slip, horizontal relative displacement

1. INTRODUCTION

Shear connector is important for steel-concrete composite structures. It is used as a shear resistance in the steel-concrete interface. The equations to predict the load carrying capacity of shape steel shear connector and single plate shape shear connector were already proposed by (Kiyomiya and Yokota 1986) and (Ueda and Chin 1991) respectively. Also (Saidi et al. 2008) proposed an equation to predict the transferred shear force at a sudden decrease of equivalent stiffness of shape steel shear connector. Also, the formulas for shear capacity of L-shape shear connectors and steel-concrete sandwich members are available in the Design Code of Steel-Concrete Sandwich Structure (JSCE 1992). However, in design of
steel-concrete composite members against shear force, the capacity of compressive strut in front of the shear connector is important. The compressive strut capacity of L-shape shear connector depends on the dimensions of the shear connector and the concrete strength. Therefore, by means of beam type test method (Soty and Shima 2009), this study proposed an equation to predict the maximum shear force on L-shape shear connector at failure of compressive strut in front of the shear connector. Also, shear force-slip relationships and shear force-horizontal relative displacement relationships of L-shape shear connector were discussed in this study.

2. EXPERIMENT

2.1 Specimens

Four beam type specimens were constructed identically to replicate a part of a possible steel-concrete composite structure whose shear connectors were installed with strut angle approximately 45 degrees. The specimens, symbolized as S-h-h_sc-t1,sc-fc', are given in detail in Figure 1 and Table 1. The sizes of the specimen were increased with the sizes of the shear connectors and shear span-to-depth ratio of every specimen was constant. JIS G3101 standard steel with grade SM490 and grade SS400 was used for the steel plate and the shear connector respectively.

| Specimens | Sizes of specimens (mm) | Sizes of shear connectors (mm) | Thickness of skin plate | Concrete strength |
|-----------|-------------------------|--------------------------------|-------------------------|-------------------|
|           | a | b  | h | h_sc | w | t1,sc | t2,sc | t_f  | f_c' |
| S-600-200-9-38 | 510 | 150 | 600 | 200 | 90 | 9 | 14 | 9 | 38 |
| S-600-200-9-25.3 | 510 | 150 | 600 | 200 | 90 | 9 | 14 | 9 | 25.3 |
| S-450-150-9-23.6 | 410 | 150 | 450 | 150 | 75 | 9 | 14 | 9 | 23.6 |
| S-300-100-9-25.1 | 290 | 150 | 300 | 100 | 50 | 9 | 14 | 9 | 25.1 |

2.2 Measurement

Strain gauges were attached on both sides of the concrete surface and steel plate in front of the shear connector as shown in Figure 2, left side. Meanwhile, slip and horizontal relative displacements of the shear connectors were measured by means of the displacement transducers LD1-LD6, middle, and LD11-
LD12, right side, respectively. During the test, a steel plate was inserted between the steel plate of the specimen and the support for the magnetic bases and also the support shown in Figure 1. The inserted steel plate and the steel plate of the specimen easily rotated as one on the roller; therefore, the effect of the direct support on the mechanism of the shear connector can be minimized. On the other hand, the specimens were stable enough even though the supports were modified.

![Fig. 2: Locations of strain gauges and displacement transducers](image)

3. RESULTS AND DISCUSSIONS

3.1 Mode of failure

All specimens failed when splitting crack took place in the core concrete in front of the shear connector, split failure, without break of shear connector. As shown in Figure 3 and Figure 4, three steps of cracking in the concrete were observed—flexural crack at mid span, crack from head of the shear connector, and splitting crack in front of the shear connector. Since all specimens failed at the left size of the specimens, this study focuses only on the left size shear connectors.
3.2 Maximum shear force on L-shape shear connector

Shear force was calculated by multiplying stress in the steel plate ($\sigma = Ee$) in front of the shear connector with the area of the steel plate ($A = t_f \times b$) that strain values ($e$) were obtained from the strain gauges on the steel plate (L11-L16) shown in Figure 2. As shown in Figure 5, shear forces ($V$) were found all almost the same as loads ($P$).

Figure 6 shows the relationships between shear force and principal tensile strain in concrete at which splitting crack took place of every specimen. It can be seen that shear forces on the shear connectors suddenly dropped when splitting crack occurred. Therefore, it can be said that splitting crack occurrence in the core concrete controlled the maximum shear force on the shear connector. Table 2 lists the maximum shear forces obtained from the experiments $V_{\text{max}, \text{exp}}$ and the calculations by means of the formulas in the design code for steel-concrete sandwich structure of (JSCE 1992). The calculations of shear strength and shear capacity of the specimens were made with safety factors 1.0. It can be seen that $V_{\text{max}, \text{exp}}$ were smaller than the calculated shear strengths of the shear connectors $V_{sc2}$ for all specimens. That was the reason why no break of shear connector was observed during the experiments. Meanwhile, good agreements between the calculated shear capacities of L-shape shear connectors $V_{sc1}$ and $V_{\text{max}, \text{exp}}$ were observed with $V_{\text{max}, \text{exp}}$ to $V_{sc1}$ ratios equal to 1.02 to 1.11. However, when the strut angle was assumed to be 30° as recommended by the code (JSCE 1992), shear capacity of beam type specimens $V_{u2}$ were smaller than $P_{\text{max}, \text{exp}}$ ($P_{\text{max}, \text{exp}} = V_{\text{max}, \text{exp}}$) which $P_{\text{max}, \text{exp}}$ to $V_{u2}$ ratios varied from 1.45 to 1.65. On the contrary, when the strut angle was assumed to be 45° which is identical to the experimental conditions, the calculated shear capacity $V_{u2}$ was greater than $P_{\text{max}, \text{exp}}$ with $P_{\text{max}, \text{exp}}$ to $V_{u2}$ ratio varied from 0.72 to 0.82. These results prove the commentary in the design code for steel-concrete sandwich structures of (JSCE 1992) stating that the shear capacity of the steel-concrete composite members calculated through the code is too conservative when the ratio of shear span to effective depth $a/d$ is small or when the tension reinforcing steel plate is thick.
Figure 7 shows a model of the shear connector subjected to strut compressive force after the occurrence of crack from the head of the shear connector. \( h' \) is the height of confining concrete against the shear connector and \( X_c \) is the width of strut \((X_c = h' \times \sqrt{2})\). It is assumed that the behavior of the concrete block in front of the shear connector is the same as the cylinder with diameter \( X_c \) in the split tensile strength test as shown in Figure 7. Therefore, equation (1) can represent the model when splitting crack occurred in the concrete in front of the shear connector:

\[
f_t = \frac{2 \times \sqrt{2} \times V_{\text{max}}}{\pi \times X_c \times b_{sc}}
\]

\[
\Rightarrow V_{\text{max}} = 0.5 \times \pi \times h' \times b_{sc} \times f_t
\]

Since \( f_t = 0.44 \sqrt{f_c'} \), equation (2) can be represented by equation (3) as follows:

\[
V_{\text{max}} = k \times b_{sc} \times h_{sc} \times \sqrt{f_c'}
\]

Table 2: Experimental and calculation results

| Specimens       | \( V_{\text{max,exp}} \) (kN) | \( V_{\nu,1} \) (kN) | \( V_{\nu,2} \) (kN) | \( V_{\nu,1} \) \( \theta = 30^\circ \) (kN) | \( V_{\nu,2} \) \( \theta = 45^\circ \) (kN) | \( V_{\text{max,exp}} \) \( V_{\text{sc,1}} \) | \( V_{\text{max,exp}} \) \( V_{\text{sc,2}} \) | \( P_{\text{max,exp}} \) \( V_{u,1} \) | \( P_{\text{max,exp}} \) \( V_{u,2} \) | \( V_{\text{max,exp}} \) \( V_{\text{max,cal}} \) |
|-----------------|-------------------------------|----------------------|----------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-------------------------------|-------------------------------|---------------------------------|
| S-600-200-9-38  | 266                           | 240                  | 274                  | 170                            | 340                            | 254                             | 1.11                            | 0.97                           | 1.56                           | 0.78                           | 1.05                            |
| S-600-200-9-25.3 | 200                           | 195                  | 274                  | 138                            | 276                            | 206                             | 1.02                            | 0.73                           | 1.45                           | 0.72                           | 0.96                            |
| S-450-150-9-23.6 | 180                           | 171                  | 274                  | 118                            | 237                            | 182                             | 1.06                            | 0.66                           | 1.54                           | 0.77                           | 0.98                            |
| S-300-100-9-25.1 | 170                           | 154                  | 274                  | 103                            | 206                            | 169                             | 1.11                            | 0.62                           | 1.65                           | 0.82                           | 1.00                            |
That $k = 0.22 \times \pi \times (h'/h_{sc})$ is a constant representing all effected factors. By means of experimental data, Figure 8 gives the relationship between $k$ and $t_{1,sc}/h_{sc}$. Therefore, the equation for maximum shear force on L-shape shear connector at splitting crack occurrence can be expressed as follows:

$$V_{\text{max}} = \left(19.56 \times \frac{t_{1,sc}}{h_{sc}} + 0.494\right) \times b_{sc} \times h_{sc} \times \sqrt{f'_c}$$

where $V_{\text{max}}$ is the maximum shear force at splitting crack occurrence in (N), $b_{sc}$ is the width of the shear connector in (mm), $h_{sc}$ is the height of the shear connector in (mm), $t_{1,sc}$ is the thickness of the shear connector in (mm), and $f'_c$ is concrete compressive strength in (N/mm²).

As listed in Table 2, it can be seen that the maximum shear force at splitting crack occurrence calculated by means of equation (3) $V_{\text{max,cal}}$ agreed well with experimental results with $V_{\text{max,exp}}/V_{\text{max,cal}}$ ratio varied from 0.96 to 1.05. This agreement proves the reliability of the equation.

3.3 Shear force and slip relationships

The average value obtained from the displacement transducers (LD1 to LD6) shown in Figure 2 was determined as slip between concrete and steel plate. It can be seen in Figure 9 that all the curves of shear
force-slip relationship are almost the same, therefore, no effect of concrete strength and the height of shear connector on shear force-slip relationships was observed. Moreover, after splitting crack occurrence, the values of slip were detected negatively which meant that the occurrence of splitting crack reversed the direction of the slip. As shown in Figure 10, when the head of the shear connector displaced until $\delta_{\text{max}}$ and strain in the concrete transformed to the principal direction, splitting crack took place along the principal angle $\theta_p$. It can be said that the relative displacement of the shear connector made the core concrete released the stress leading to splitting crack occurrence.

3.4 Shear force $V$ and horizontal relative displacement $\delta$ relationships

Since the shear force-horizontal relative displacement relationships could be clearly observed only in S-600-200-9-25.3 and S-300-100-9-25.1, the discussions were accordingly conducted. As shown in Figure 11, the values of $\delta$ in S-600-200-9-25.3 were detected negatively when the levels of shear force were less than 150kN. Similar behaviors were also observed in the steel-concrete sandwich beams by (Makabe et al. 1992) that under low level of shear force, the head of the shear connector moved forward (negative) and it moved backward (positive) when levels of the shear force became higher. However, it was observed during the experiment that at 150kN crack took place in the concrete from the head of the shear connector; therefore, it seemed that the occurrence of this crack induced backward movement of the head of the shear connector. On the other hand, it can be observed in Figure 12 that after the occurrence of the crack from the head of the shear connector, big increment of $\delta$ with small increments of $V$ were observed. Meanwhile, the specimen with the larger size shear connector failed with greater value of $\delta$ than that with the smaller size shear connector.

![Figure 11: $V - \delta$ relationship before crack occurred from head of shear connector](image1)

![Figure 12: $V - \delta$ relationships of S-600-200-9-25.3 and S-300-100-9-25.1](image2)

4. FEM ANALYSES

Finite element analyses were conducted to verify the experimental results. There were three material types for the elements: plain concrete, steel, and bond link or joint element. Based on elasto-plastic and fracture model (Okamura and Maekawa 1997), a constitutive model for the concrete before cracking was constructed. Meanwhile, a constitutive model of cracked concrete consisted of tension stiffening,
compression and shear transfer model. A two-dimensional failure criterion in tension-tension and compression-tension was applied to the analyses. Since steel plates and shear connectors were in elastic ranges until failure of the specimens, elastic plate was selected to be steel plate and shear connector in the analyses. Bond link element was originated from a linear bond stress-slip relationship and it was applied along the contact between the steel and the concrete. Bond link element’s normal stiffness in compression direction was maintained a great value, 300 times greater than the shear stiffness in order to avoid element overlap. Meanwhile, the stiffness in tension was maintained a low value for easy parting between the steel elements and the concrete elements. As shown in Figure 13, left side, the flexural crack and the crack from the head of the shear connector were accordingly introduced to make it agree with the conditions of the tested specimens. Figure 13, right side, shows that the occurrence of splitting crack in the concrete elements in the analyses agreed well with that in the tested specimens. Moreover, $V - \delta$ relationships obtained from the FEM analyses and the experiments were compared as shown in Figure 14. It can be seen that the results obtained the FEM analyses agreed well with those of the experiments for mode of failure, the maximum shear force on the shear connector, and shear force-horizontal relative displacement relationships.

![Figure 13: FEM mesh (left side) and S-600-200-9-25.3 in FEM analysis and experiment](image)

![Figure 14: $V - \delta$ relationships obtained from experiments and FEM analyses](image)
5. CONCLUSIONS

The following conclusions can be derived from this study.

1) The occurrence of splitting crack in the concrete in front of the shear connector was found to control the maximum shear force on L-shape shear connector subjected to strut compressive force. Meanwhile, the maximum shear forces of the specimens were found to be less than the calculation by means of JSCE Code when strut angle was assumed to be 45 degrees, but were greater than the calculation when the strut angle was assumed to be 30 degrees.

2) An equation to predict the maximum shear force on L-shape shear connector at the occurrence of splitting crack is proposed to be

\[ V'_{\text{max}} = \left(19.56 \times \left(\frac{t_{\text{sc}}}{h_c}\right) + 0.494\right) \times b_c \times h_c \times \sqrt{f'_c}. \]

3) The horizontal relative displacements of L-shape shear connectors were found to have big increment with small increment of shear force after the occurrence of crack in the concrete starting from the head of the shear connector. Also, the occurrence of splitting crack in the concrete in front of the shear connector was found to reverse the direction of the slip between concrete and steel plate in front of the shear connector.

4) The results obtained from FEM analyses were found to agree with the experimental results for the maximum shear forces on L-shape shear connector at splitting crack occurrence and the relationships between shear force and horizontal relative displacement.

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References

[1] Kiyomiya O and Yokota H (1986). Strength of shear connector by shape steel in composite member with steel and concrete, Proc. of Symposium on Research and Application of Composite Constructions, JSCE, pp.113-118.
[2] Ueda T and Chin CK (1989). Strength of steel plate shear connector, Proc. of the Second Symposium on Research and Application of Composite Constructions, Kobe, Japan, pp.149-156.
[3] Saidi T, Furuuchi H, and Ueda T (2008). The transfer shear force-relative displacement relationship of the shear connector in steel-concrete sandwich beam and its model, Doboku Gakkai Ronbunshuu, E, Vol.64, No.1, pp.122-141.
[4] JSCE Research Subcommittee on Steel-Concrete Sandwich Structures (1992). Design code for steel-concrete sandwich structures – Draft, Concrete Library of JSCE, No. 20, pp.1-21.
[5] Soty R and Shima H (2009), A new beam type test method for load-slip relationship of L-shape shear connector, 8th national symposium, JSCE, Tokyo.
[6] Makabe T, Malek N, Mutsuyoshi H, and Machida A (1992). Experimental Study on Mechanical Properties of Steel and Concrete Sandwich Beam, J. of Structural Div., JCI, Vol.14, pp 729-733.
[7] Okamura H and Maekawa K (1997). Nonlinear Analysis and Constitutive Models of Reinforced Concrete, Japan.