*-Technical Paper-*

# BEHAVIORS OF L-SHAPE SHEAR CONNECTOR SUBJECTED TO STRUT COMPRESSIVE FORCE IN BEAM TYPE TEST SPECIMENS

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ABSTRACT
This study investigates the behaviors of L-shape shear connector subjected to strut compressive force in steel-concrete composite structure. It was found that splitting crack in the concrete in front of the shear connector controlled the maximum shear force on the shear connector. After crack occurred in the concrete starting from the head of the shear connector, the shear connector started to have large displacements until occurrence of splitting crack. Moreover, occurrence of splitting crack was found to reverse the direction of the slip between concrete and steel plate in front of the shear connector.
Key words: L-shape shear connector, splitting crack, maximum shear force, slip, relative displacement

## 1. INTRODUCTION

Several researches have been conducted to study the relationship between shear force and slip of shear connector in steel-concrete composite structure. The test methods which represent real structure have been tried to use. Saidi et al. [1],[2] investigated shear force-relative displacement relationship of shear connector in steel-concrete sandwich beam and proposed a model for initial stiffness of shear connector and its curvature. Makabe et al. [3] studied the mechanical properties of steel-concrete sandwich beam and illustrated the behaviors of L-shape shear connector with respect to shear force. However, only small-size shear connectors were investigated. Differently, Ros and Shima [4] developed a new beam type test method for shear force and relative displacement relationship of large-size L-shape shear connector in steel-concrete composite structure. It has been observed in both sandwich beam and beam type specimens that maximum shear force on shear connector seems to be effected by occurrence of diagonal crack in concrete. Therefore, the focus of this study is to determine the most critical factor controlling maximum shear force and shear force-relative displacement relationship of L-shape shear connector in steel-concrete composite structure.

## 2. EXPERIMENT

### 2.1 Specimens

Four beam type specimens [4] with different sizes of shear connectors and concrete strengths were tested. Height of the beam type specimen was three times that of the shear connector. Sizes of the specimens were increased with sizes of the shear connector and shear span-to-depth ratio of the specimen was constant. The specimens were symbolized as S-height of specimen-height of shear connector-concrete strength (S-600-200-38). Table 1 gives the properties of the steel used in the experiment and Table 2 & Fig.1 show the details of the beam type specimens.

Table 1 Characteristics of steel

| Types | Shear Connector | Skin Plate |
|---|---|---|
| Tensile yield strength $f_y$ $(N/mm^2)$ | 352 | 370 |
| Ultimate strength $f_u$ $(N/mm^2)$ | 448 | 511 |
| Module elasticity $E$ $(kN/mm^2)$ | 202 | 204 |

Table 2 Detail of specimens

| Specimens | Sizes of specimen (mm) | | | Sizes of shear connector (mm) | | | | Thickness of skin plate | Concrete strength $f'_c$ |
|---|---|---|---|---|---|---|---|---|---|
| | $a$ | $b$ | $h$ | $h_{sc}$ | $w$ | $t_{1,sc}$ | $t_{2,sc}$ | $t_f$ (mm) | $(N/mm^2)$ |
| S-600-200-38 | 510 | 150 | 600 | 200 | 90 | 9 | 14 | 9 | 38 |
| S-600-200-25.3 | 510 | 150 | 600 | 200 | 90 | 9 | 14 | 9 | 25.3 |
| S-450-150-23.6 | 410 | 150 | 450 | 150 | 75 | 9 | 14 | 9 | 23.6 |
| S-300-100-25.1 | 290 | 150 | 300 | 100 | 50 | 9 | 14 | 9 | 25.1 |

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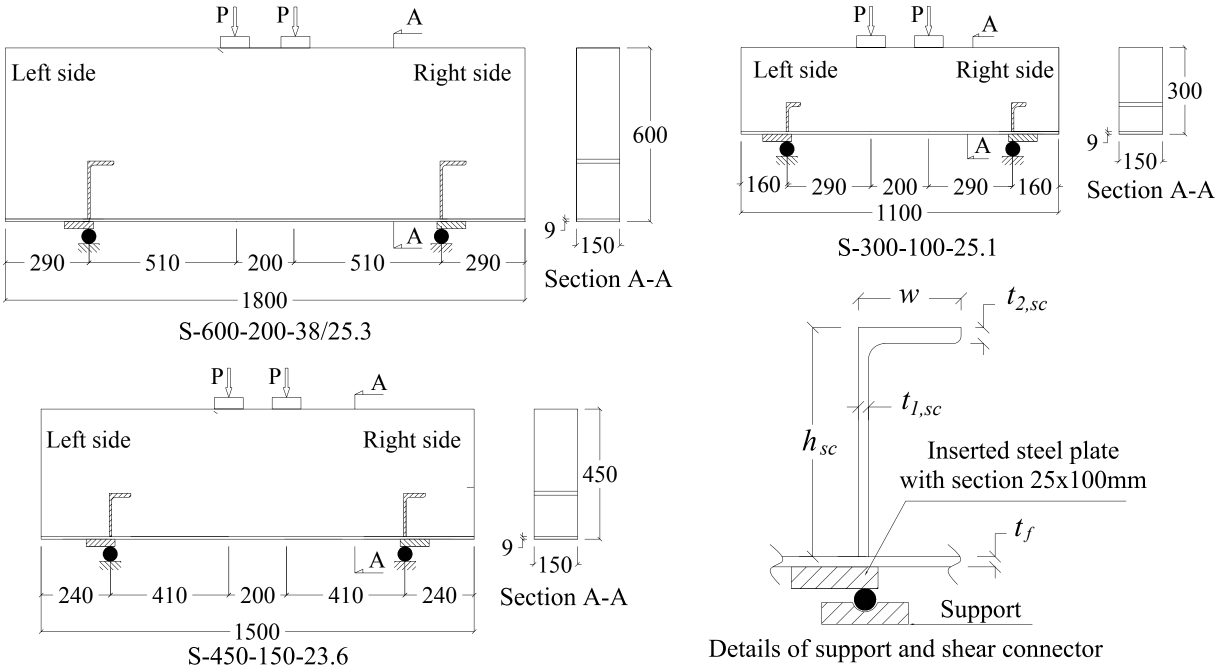


Fig.1 Details of the beam type specimens

## 2.2 Measurement set up

Strain gauges (L11 to L16) were attached on both sides of the steel plate surface in front of the shear connector in order to estimate strain distribution in the steel plate, Fig.2. Strain gauges were also attached on both sides of the concrete surface as shown in Fig.3 to measure the development of strain in the concrete in front of the shear connector. Strain gauge L39, L41, and L43 were attached on the concrete surface at opposite sides of L40, L42, and L44 respectively. The distribution of slip between the concrete and the steel plate in front of the shear connector was measured by means of the displacement transducers as illustrated in Fig.4. Also, mid span deflections were measured by means of the displacement transducers (LD7-LD8). Furthermore, two displacement transducers (LD11-LD12) were installed to measure horizontal relative displacements between the top and the bottom of the shear connector as shown in Fig.5. The measurement equipments were left-right installed symmetrically in pairs in all specimens. During the experiment, another steel plate was inserted between the steel plate of the specimen and the support for the magnetic bases and for support. As shown in Fig.1, this steel plate and the steel plate of the specimen easily rotated as one on the roller. Therefore, the behavior of the shear connector is reasonably identical with the real structure. The horizontal displacements due to the rotation of the steel plate were also considered in the relative displacement of the head of the shear connector. Even though the supports were modified, the specimens were observed to be stable during the experiments.

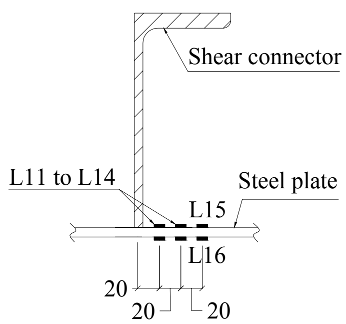


Fig.2 Strain gauges attached on steel plate surface

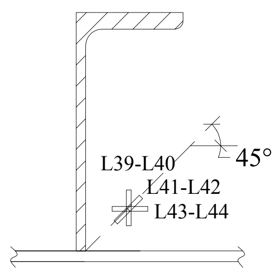


Fig.3 Strain gauges attached on concrete surface

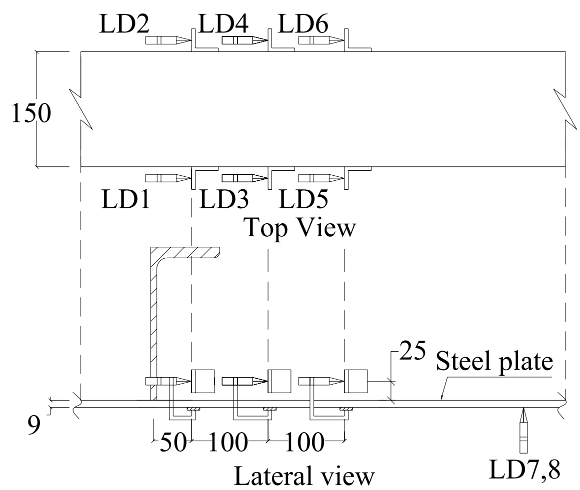


Fig.4 Slip distribution measurement

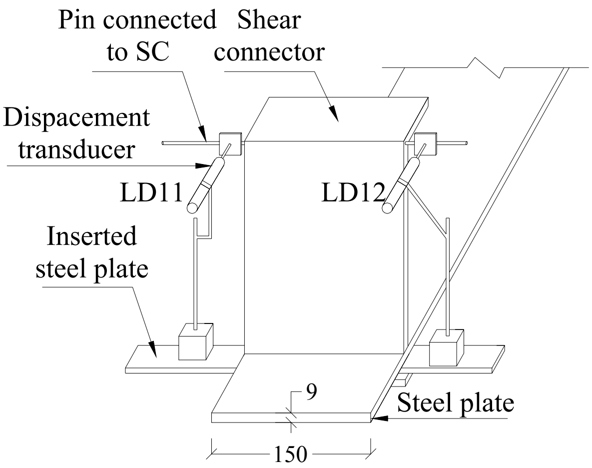


Fig.5 Relative displacement measurement

## 3. RESULTS AND DISCUSSIONS

### 3.1 Mode of failure

All specimens failed when splitting crack occurred (split failure) in the concrete starting from the toe of the shear connector to the loading point. Split failures took place at the left and right sides of specimen only in S-450-150-23.6. No failures occurred at the right side of the three other specimens. Before failure, three stages of cracking in concrete were observed. Firstly, flexural crack took place at mid span and propagated almost vertically. Secondly, crack in concrete starting from the head of the shear connector to the loading point. Finally, splitting crack occurred in concrete starting from the toe of the shear connector to the loading point at an angle of approximately 45$^o$ with the member's horizontal axis. Split failure took place with different load levels, 296kN, 210kN, 182kN, and 170kN in S-600-200-38, S-600-200-25.3, S-450-150-23.6, and S-300-100-25.1 respectively. Fig.6 shows crack pattern in specimen S-600-200-25.3 at failure; and Fig.7 shows crack patterns in the beam type specimens.

Moreover, it was observed that break of shear connector did not occur in specimens. Since all specimens failed at left side shear connectors, only left side shear connectors were focused in this study.

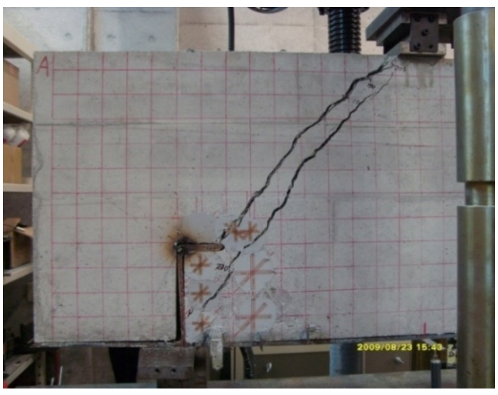

Fig.6 Crack pattern at failure in S-600-200-25.3

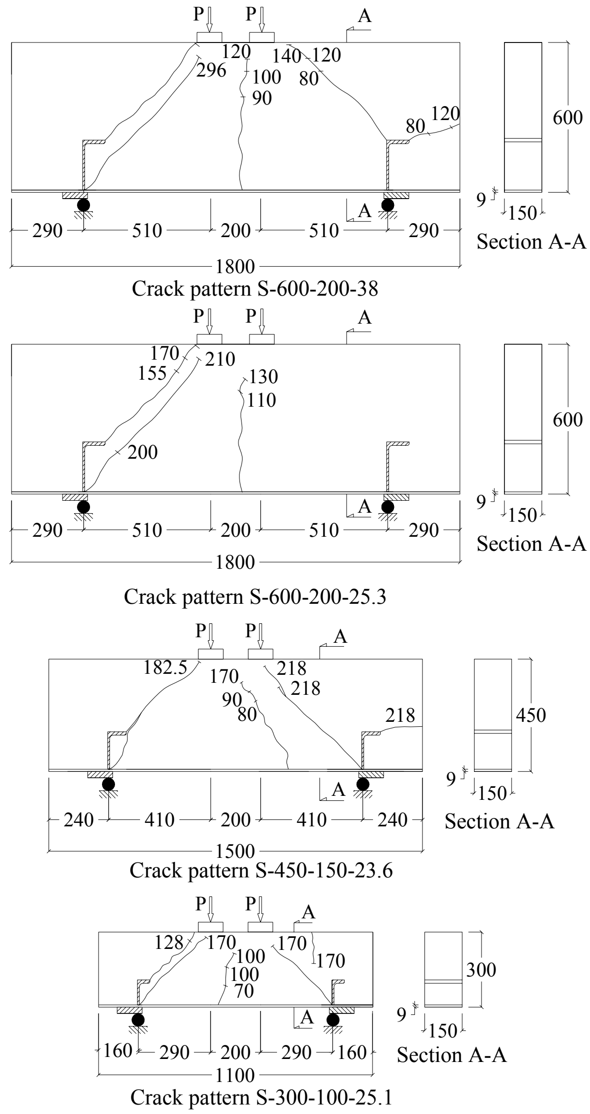


Fig.7 Crack patterns at failure in the specimens

### 3.2 Shear force

Shear force was calculated by multiplying stress in the steel plate in front of the shear connector $(\sigma)$ with the area of the steel plate $\left(A = t_f . b\right)$. Meanwhile, stress in the steel plate was calculated by means of stress-strain relationship in the steel plate $(\sigma = E\varepsilon)$ that strain values were obtained from the strain gauges shown in Fig.2. Shear force (V) were found the same as load (P) except that in S-600-200-38.

### 3.3 Shear force-slip relationship

Average value obtained from the displacement transducers (LD1 to LD6) shown in Fig. 4 was determined as slip between concrete and steel plate in front of shear connector. Fig.8 gives shear force-slip relationships of the shear connectors in all specimens. It can be seen that the curves of shear force-slip relationships in S-600-200-38, S-600-200-25.3, and S-450-150-23.6 were almost the same; therefore, no effect of concrete strength and height of the shear connector on shear force-slip relationship was observed. Moreover, it can be observed in S-600-200-25.3 and S-300-100-25.1 that after crack took place in the concrete

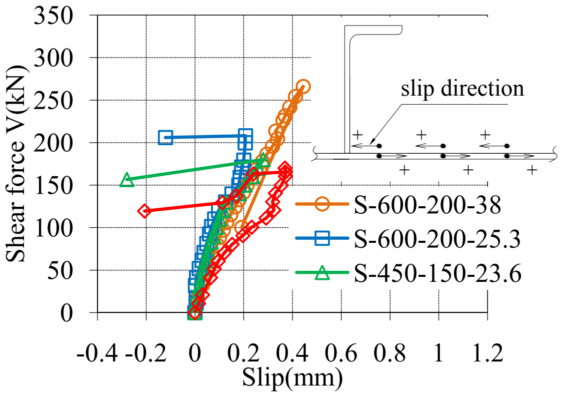


Fig.8 Shear force-slip relationships

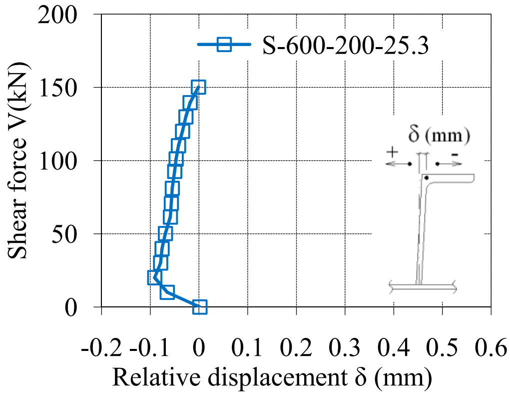


Fig.9 Shear force-relative displacement relationship before cracking from head of shear connector

starting from the head of the shear connector, small increments of the slip were detected until splitting crack occurred in the concrete in front of the shear connector. This indicated stress in the concrete in front of the shear connector became higher after crack occurred in the concrete starting from the head of the shear connector. Furthermore, as shown in Fig.8, when the splitting crack occurred, the values of the slip were detected negatively. Therefore, it can be said that occurrence of the splitting crack reversed the direction of slip between concrete and steel plate in front of the shear connector.

### 3.4 Shear force-relative displacement relationship

Since the relationships between shear force and relative displacement could be clearly observed only in S-600-200-25.3 and S-300-100-25.1, the discussions were accordingly conducted. As shown in Fig.9, the relative displacements of the L-shape shear connector in S-600-200-25.3 were detected negatively when the shear forces were less than 155kN. Similar behaviors were also observed in the steel-concrete sandwich beams by Makabe et al. [3] 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 has been observed during the experiment that at 155kN crack occurred in the concrete starting from the head of the shear connector; therefore, it seemed that the occurrence of this crack lead to backward movement of the head of the shear connector.

Fig.10 shows shear force-relative displacement relationships of the shear connectors. It is observed that the relative displacements of the head of the shear connectors before occurrences of crack in the concrete starting from the head of the shear connectors were very small. The sudden increase of the relative displacement at low level of shear force in S-300-100-25.1 was due to unexpected sudden rotation of the inserted steel plate before it fully touched the steel plate of specimen. On the other hand, after occurrence of the crack in the concrete starting from the head of the shear connector, big increments of the relative displacements with small increments of shear force were observed until splitting crack occurred in the concrete in front of the shear connector. Moreover, it was observed that the specimen with larger size shear connector failed with greater value

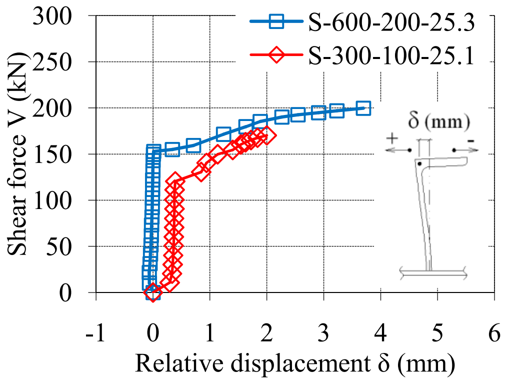


Fig.10 Shear force-relative displacement relationships

of the relative displacement than the specimen with smaller size shear connector. The values of the relative displacements found in the tested specimens were greater than those in steel-concrete sandwich beam by Saidi et al. [1],[2]. Failure of sandwich beam before the shear connector gives large relative displacement may be the reason for this difference.

### 3.5 Splitting crack and maximum shear force

It has been observed during the experiment that splitting crack occurrence in the concrete in front of the shear connector seemed to control maximum shear force. Therefore, the relationships between shear forces and principal tensile strains in the concrete where the splitting crack occurred were observed. The principal tensile strain, $\varepsilon_{pt}$ and the principal angle $\theta_p$ were calculated from strain values obtained from the strain gauges shown in Fig.3. It can be seen in Fig.11 that shear forces suddenly decreased when the principal tensile strains in the concrete reached certain values. It can be said that shear force suddenly decreased when splitting crack occurred. Fig.12 gives principal angle-principal tensile strain relationship in the concrete where splitting crack occurred. It can be seen clearly that the values of the principal angle, $\theta_p$ were the same as the direction of the splitting crack. Fig.13 shows the conditions of the shear connector and the concrete when splitting crack occurred in front of the shear connector.

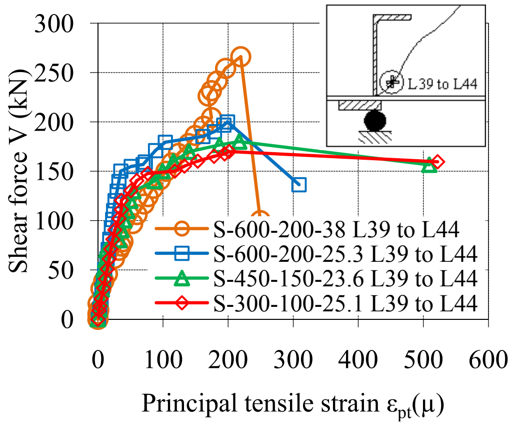


Fig.11 Shear force-principal tensile strain relationships

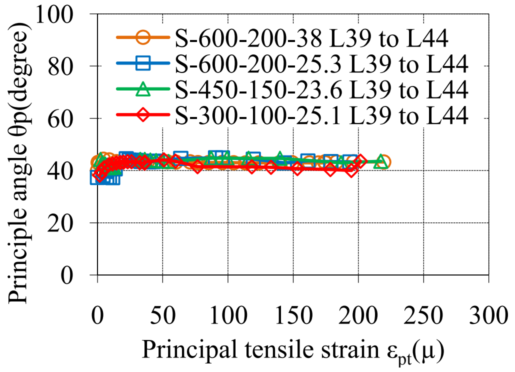


Fig.12 Principal angle-principal tensile strain relationships

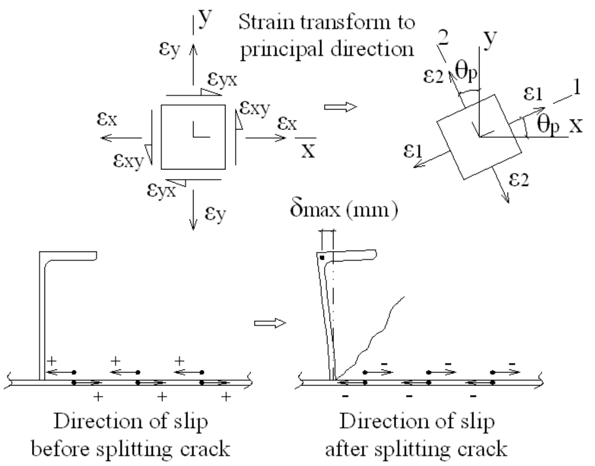


Fig.13 Conditions of shear connector and concrete when splitting crack occurred

## 4. FEM ANALYSIS

Finite element analysis was conducted to verify the experimental results. There were three material types for the element such as plain concrete, steel and bond link or joint element. By means of elasto-plastic and fracture model [5], a constitutive model for the concrete before cracking was constructed. Also, a constitutive model for concrete after cracking consisted of tension stiffening, compression and shear transfer model [5]. In the analysis, a two-dimensional failure criterion [5] in tension-tension and compression-tension was applied. Since the steel plate and the shear connector were still in elastic ranges until failure of the specimens, elastic plate was selected and assumed to be the steel plate and the shear connector in the analysis. Bond link element was originated from a linear bond stress-slip relationship. It was applied along the contact between the steel and the concrete. Bond link element's normal stiffness in compression direction was kept with a big value which was 300 times greater than shear stiffness in order to avoid from elements overlapping. Meanwhile, the stiffness in tension was kept with small value with the aim of easy parting between the steel elements and concrete elements. As shown in Fig.14, in the analysis, the flexural crack and the crack in the concrete starting from the head of the shear connector were accordingly introduced to make it agree with the experimental results.

Fig.15 shows that the condition of the concrete elements at failure in the analysis agreed with that in experiment. Moreover, Fig.16 and Fig.17 show good agreements between the analysis and the test results for

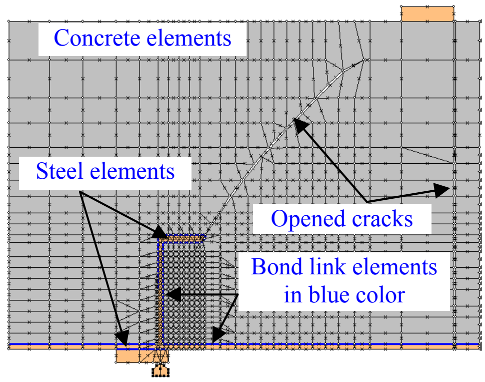


Fig.14 Finite element mesh S-600-200-25.3

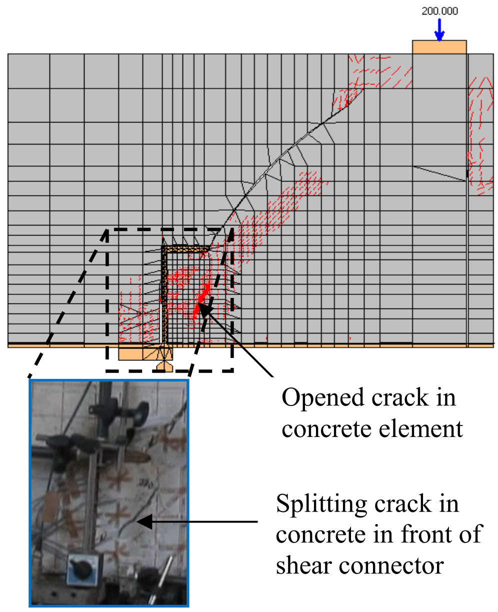


Fig.15 Opened crack in S-600-200-25.3 at 200kN

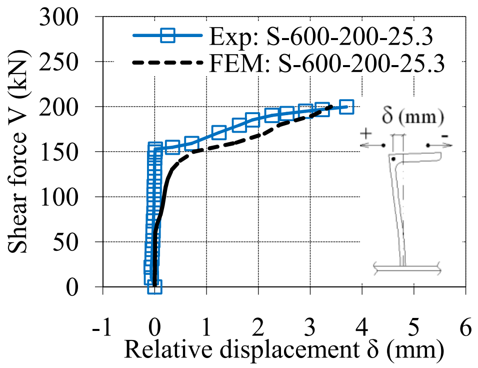


Fig.16 Shear force-relative displacement relationship S-600-200-25.3

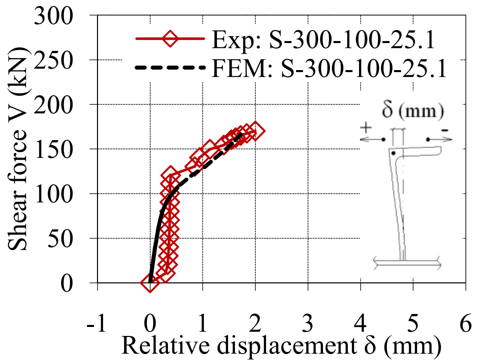


Fig.17 Shear force-relative displacement relationship S-300-100-25.1

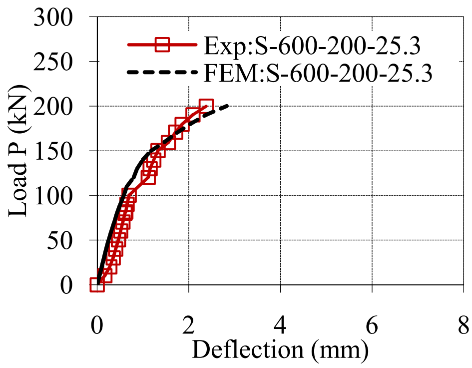


Fig.18 Load-deflection relationship S-600-200-25.3

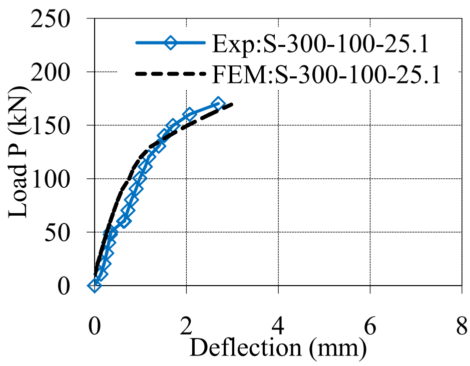


Fig.19 Load-deflection relationship S-300-100-25.1

the shear force-relative displacement relationships and maximum shear force on the shear connector. Moreover, Fig.18 and Fig.19 show good agreements between the load-deflection relationships obtained from the experiment results and the FEM analysis results.

## 5. CONCLUSIONS

The following conclusions can be derived from this study.

(1) Splitting crack in the concrete in front of the shear connector was found to control the maximum shear force on the shear connector.

(2) The head of shear connector was found to have large relative displacements after crack occurred in the concrete starting from the head of the shear connector.

(3) In the specimen with large size shear connector, splitting crack occurred at higher levels of shear force and greater value of relative displacement than in that with smaller size shear connector.

(4) Splitting crack was found to reverse the direction of the slip between concrete and steel plate in front of the shear connector.

(5) The results obtained from FEM analysis were found to agree with experimental results for the shear force-relative displacement relationships, load-deflection relationships and maximum shear forces on the shear connector.

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