Journal of Structural Engineering Vol.45A(March 1999) JSCE

EFFECTS OF SHAPE AND LOCATION OF SHEAR CONNECTOR ON ITS TRANSFERRED SHEAR FORCE AND RELATIVE DISPLACEMENT RELATIONSHIP IN STEEL-CONCRETE SANDWICH BEAM

Taufiq SAIDI*, Hitoshi FURUUCHI** and Tamon UEDA***

* Graduate Student, Div. of Structural and Geotechnical Eng., Hokkaido University, Sapporo 060-8628
** Member of JSCE, Research Associate, Div. of Structural and Geotechnical Eng., Hokkaido University, Sapporo 060-8628
*** Member of JSCE, Associate Professor, Div. of Structural and Geotechnical Eng., Hokkaido University, Sapporo 060-8628

This study investigates the effects of the shape and location of the shaped steel shear connector on its behavior in steel-concrete sandwich beam. In this study the shear connectors not only in tensile side of the concrete (lower) but also in the compressive side (upper) were studied. The effects of the shape on the initial equivalent stiffness as well as the value of the transferred shear force when a sudden decrease of the equivalent stiffness of the shear connector and the crack propagation were presented. The revised model to predict the relationship between transferred shear force and relative displacement of the shear connector was proposed. It was found that the boundary conditions, which are no rotation at the top of the shear connector and the uniformly distributed load on the shear connector gave a good prediction of the shear connector deformation.

Keywords *: shape of the shear connector, transferred shear force, relative displacement, equivalent stiffness of shear connector*

1. INTRODUCTION

In the analysis of the steel-concrete sandwich beam structures, the composite action between steel plate and concrete should be considered by using a transferred shear force-relative displacement relationship of shear connectors. Transferred shear force and relative displacement relationships of the shear connector are affected by various factors such as the height, thickness and shape of the shear connector, concrete strength, and the thickness of the base steel plate where the shear connectors were attached. Therefore, studies by the authors[1), 2)] were conducted on the effects of the height of the shear connector and the concrete strength on the behavior of the shear connector, and the formula to predict the transferred shear force-relative displacement relationship[1)] was presented.

This paper describes the effect of the shape and location of the shear connector on the relationship between transferred shear force and relative displacement of the shear connector in steel-concrete sandwich beam. The effects of the crack propagation was investigated and the assumptions for the boundary condition of the shear connector were verified.

As a result, the revised formulae to predict the transferred shear force relative displacement relationship were proposed. A part of the test results was reported already in the previous paper[1)].

2. MODEL FOR RELATIONSHIP BETWEEN TRANSFERRED SHEAR FORCE AND RELATIVE DISPLACEMENT[1)]

In order to explain the experimental results of the relationship between transferred shear force and relative displacement of the shear connector, the equivalent stiffness was introduced[1)]. The equivalent stiffness of the shear connector is the stiffness provided by the stiffness of the shear connector itself and the concrete surrounding the shear connector.

The boundary conditions of the shear connector element in a steel-concrete sandwich beam are shown in Fig. 1; namely a fixed end at the bottom, no rotation at the top and a uniformly distributed load which balances the transferred shear force.

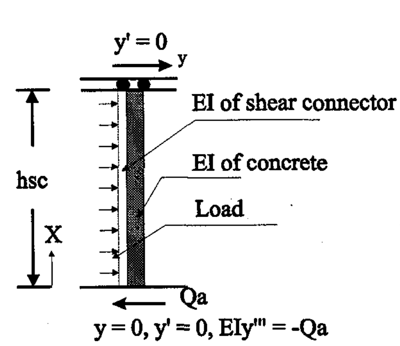

Fig. 1 The boundary conditions of the shear connector

The increment of the relative displacement of the shear connector linearly increases with the initial equivalent stiffness of the shear connector until a sudden decrease of the equivalent stiffness of the shear connector starts at a transferred shear force, Q_c. The effective stiffness of the concrete surrounding the shear connector reduces with an increase in transferred shear force.

3. OUTLINE OF EXPERIMENT

Three steel-concrete sandwich beams of rectangular cross section were tested (see Fig. 2). All the beams had the same size of 2102×150×250 mm (length × width × height). Three types of the shear connectors, namely L shape, I shape and T shape were provided at the interface between the concrete and the steel plate for specimens S-8, S-9 and S-10 respectively. It should be noted that the direction of the shear connector for specimen S-8 was in the reverse direction of the shear connector for specimen S-1 in the previous study[1)]. The sizes of the shear connectors for specimens S-8, S-9 and S-10 were L.40x40x5 mm, I.40x5 mm and T.40x40x5 mm respectively. In order to estimate the vertical compressive force in the concrete surrounding the shear connector, a tie plate was put at the same location of each shear connector and it was not welded between the tie plate and the shear connector. The vertical compressive force of the concrete is assumed the same as the tensile force of the tie plate. The specimens were designed to fail in shear compression failure mode. The details of the specimens and its shear connectors are given in Fig. 2 and Table 1.

Table 1 Details of specimens

Specimen	Type of SC	Sizes of SC (mm)**	f'_c (MPa)
S-1 *	L	40×40×5	24.2
S-2 *	L	90×40×5	24.9
S-3 *	L	140×40×5	24.9
S-8	L	40×40×5	18.3
S-9	I	40×5	21.0
S-10	T	40×40×5	31.6

SC: shear connector, *: specimens in Ref. 1)
**: first number is height and the last number is thickness

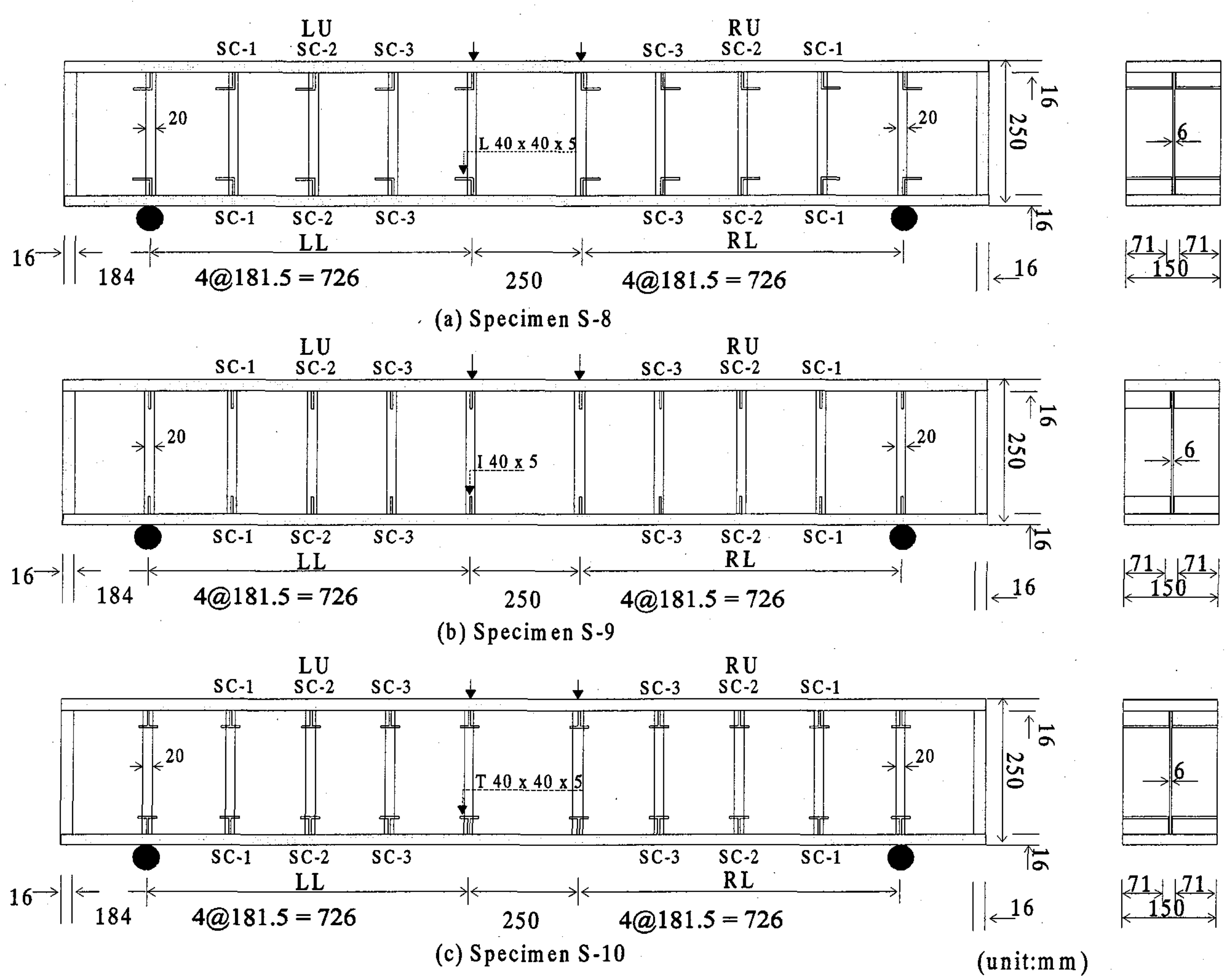

Fig. 2 Details of specimens

The steel properties for flange plate, end plate, tie plate and the shear connector were the same as in Ref. 1) as shown in Table 2.

The experimental work of this study was conducted for simply supported sandwich beams with a symmetric two-point loading system. The load was applied by a hydraulic jack and its magnitude was measured by an electrical load cell.

Table 2 Steel properties

Component	Steel type	f_y (MPa)	f_t (MPa)	E_s (GPa)
Flange Plate	SM 450 A	377.6	523.2	179
End Plate	SM 450 A	377.6	523.2	179
Tie Plate	SM 450 A	357.5	514.2	186
Shear Connector	SS 400	367.7	526.1	213

Three electrical strain gauges were mounted on both sides of the vertical part of the shear connector to measure its deformation. In order to measure the transferred shear force between concrete and lower flange plate through the shear connector electrical strain gauges were mounted on both sides of the lower flange plate near the shear connector. The gauges were also mounted on both sides of the tie plate to estimate the vertical compressive force of concrete surrounding the shear connector. Detailed arrangement of the electrical strain gauges is shown in Fig. 3.

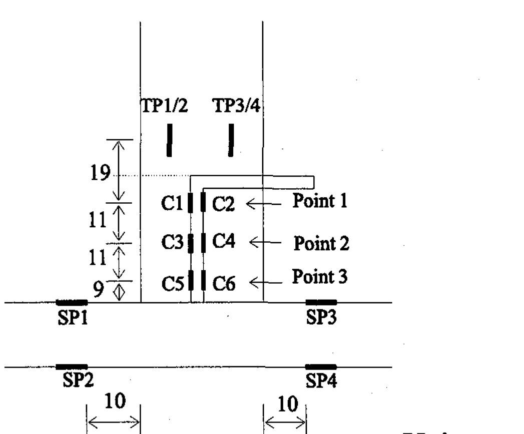

Fig. 3 Locations of strain gauges

The measuring system with contact gauges was used to measure relative displacement of the shear connector which is the relative displacement at the top of vertical part to the displacement at its bottom. The detailed arrangement of the contact gauges is given in Fig. 4

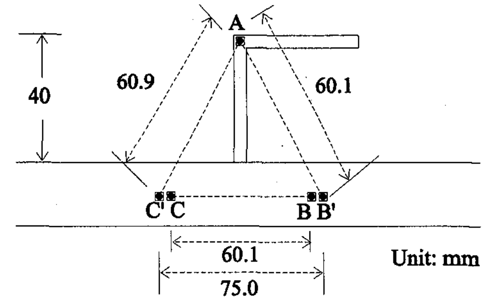

Fig. 4 Distance points measured by contact gauges

In this study the location of the shear connector was classified into four cases for each specimen namely Left Lower (LL), Right Lower (RL), Left Upper (LU), Right Upper (RU). For each location three shear connectors namely SC-1, SC-2, and SC-3 as shown in Fig. 2 were investigated. During the test, the deflection of the specimens, the relative displacement of the shear connector and the strain of the flange plate, the tie plate and the shear connector were measured at every load step. Crack propagation was observed in detail.

4. TEST RESULTS AND DISCUSSIONS

4.1 Load-deflection and failure characteristics of the beam

The load-deflection relationships for specimens S-8, S-9 and S-10 are presented in Fig. 5. Effect of the transferred shear force and relative displacement of the shear connector on the load-deflection relationship is rather small.

Figure 6 shows the crack pattern of the tested specimens. The failure mode of the beams was shear compression failure, which is characterized by diagonal cracking and crushing of the concrete near the loading point. The failure occurred in the right side of the shear span of the beam for specimens S-8 and S-10 while in the left side for specimen S-9. Some cracks also appeared at the backside of the shear connector for specimens S-8 and S-10. Those cracks propagated from the shear connector to the lower flange plate.

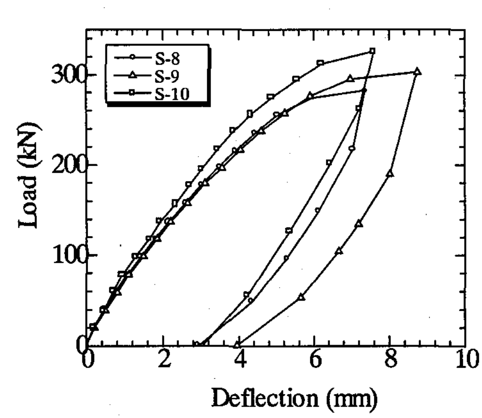

Fig. 5 Load-deflection relationship

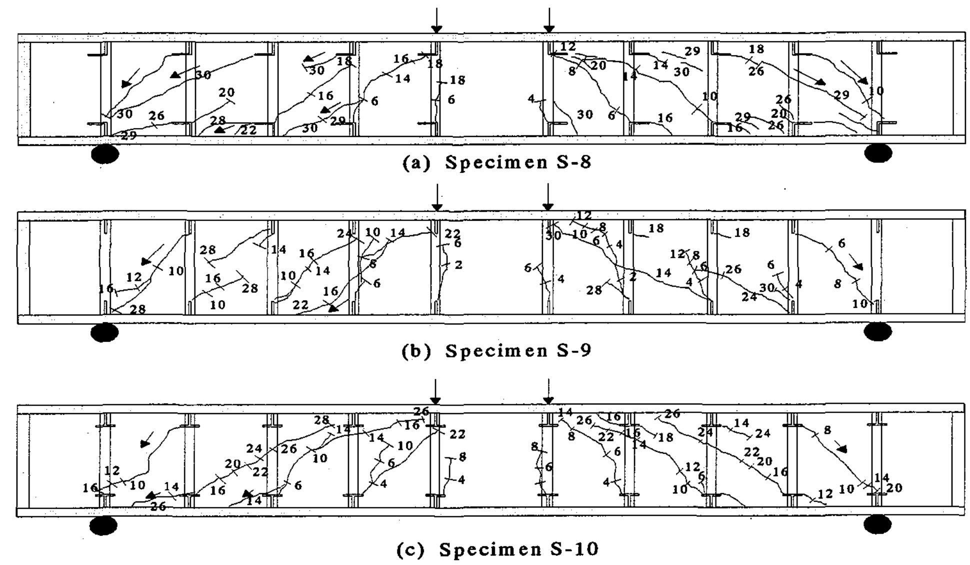

Fig. 6 Crack pattern (number indicating load in tf, 1 tf = 9.807 kN)

4.2 Relationship between transferred shear force and relative displacement

The relationship between the transferred shear force and the relative displacement at the shear connectors for specimens S-8, S-9 and S-10 are shown in Figs. 10, 11 and 12 respectively. As shown in those figures, the relationships for the upper and lower shear connectors are rather similar.

5. VERIFICATION AND REVISION OF PREVIOUS MODEL

5.1 Verification of the boundary conditions

In the previous study[1)], no rotation or spring stiffness, k infinitely large at the top of the shear connector and a fixed end at the bottom of the shear connector with uniformly distributed load which balances the transferred shear force were taken as the boundary conditions.

In this paper the above boundary conditions were verified.

The analyses for the verification of the loading condition have been done through the calculation of the curvature distribution of the shear connector with different loading condition. The curvature of the shear connector was calculated by the following equation:

$$(EI)_{eq}\, y'' = -M \qquad (1)$$

where, M : bending moment along the vertical part of the shear connector, kN-mm

y'' : curvature, mm

$(EI)_{eq}$: the equivalent stiffness of the shear connector, kN-mm^2

Three cases of the loading condition were selected. The first one was a concentrated load P at the top of the shear connector (case I), the second one was a distributed load over a portion of the vertical part of the shear connector which started from the middle of the height of the shear connector to the top of the shear connector (case II), and the third one was a distributed load over a lower haft of the vertical part of the shear connector (case III). The curvature distributions along the vertical part of the shear connector for case I, case II and case III compared with the previous assumption, which is a uniformly distributed load from the bottom to the top of the shear connector, and experimental ones are shown in Fig. 7. It can be said that the uniformly distributed load gives the best agreement with the experimental ones.

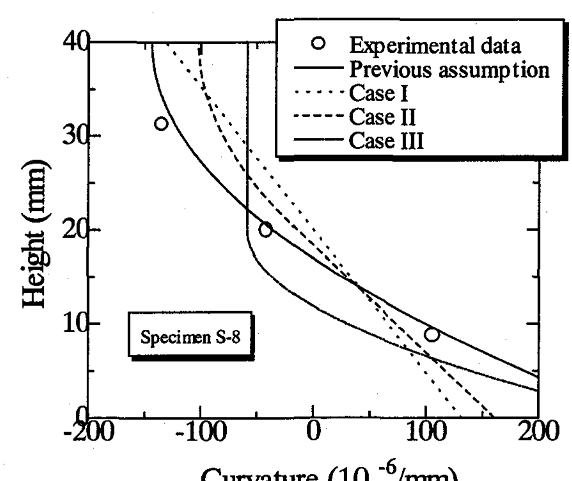

Fig. 7 Curvature distribution with different cases of the loading condition

To verify the boundary condition at the top of the shear connector the calculation of the curvature distribution of the shear connector with different spring stiffness, k was conducted. The spring was inserted at the location as shown in fig. 8.

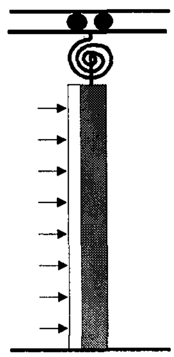

Fig. 8 Location of the spring

The spring stiffness, k was expressed as the following equation:

$$M = -ky' \qquad (2)$$

where, y' : slopes, rad
k : spring stiffness, kN-mm

Figure 9 shows the calculated curvature distribution along the vertical part of the shear connector with various k, which is compared with the case of the infinitely large k and the experimental ones.

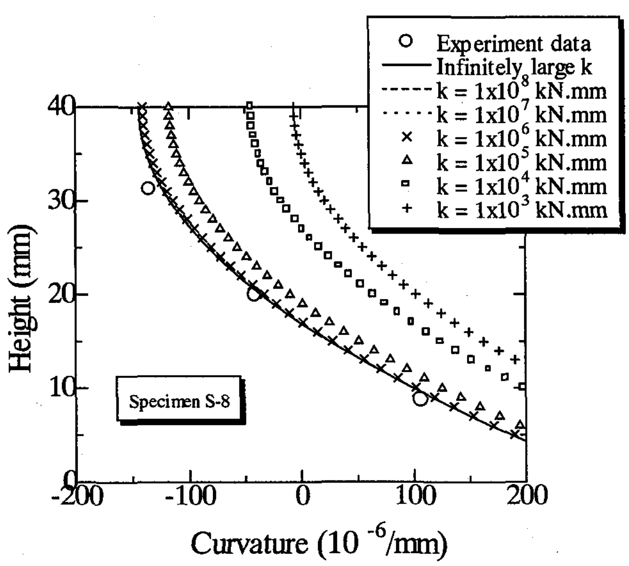

Fig. 9 Curvature distribution with different spring stiffness, k

The calculated curvature distributions for k of $1\text{x}10^7$, and $1\text{x}10^8$ are overlapped with the infinitely large k and close to the experimental ones.

It can be seen from figs. 7 and 9 that the previous assumption of the loading condition and the boundary condition at the top of the shear connector gave a good agreement with the experimental ones. Generally, a good agreement also can be seen in this relation in the cases of all the specimens including S-8, S-9 and S-10. It can be concluded that the previous assumed boundary condition, which uniformly distributed load and no rotation at the top of the shear connector can be used to analyze the transferred shear force and relative displacement of the shear connector.

However, the future study, which covers the effect of the height of the shear connector relative to the effective depth of the beam as well as the effect of the thickness of the shear connector, should be conducted. After that, it is able to conclude the applicable range more precisely.

5.2 Revision of the previous model

5.2.1 Initial equivalent stiffness of the shear connector

The equivalent stiffness of the shear connector is the summation of the stiffness of the shear connector itself and the effective stiffness of the concrete surrounding the shear connector[1)].

Table 3 shows the experimental results of the average value of the initial equivalent stiffnesses that are calculated for 12 shear connectors in each specimen. The initial equivalent stiffness was calculated from the experimental results of relationship between transferred shear force and horizontal displacement at the top of the shear connector. The effective stiffness of the concrete, $(EI)_{con}$ can be calculated by subtracting the calculated stiffness of the shear connector itself, $(EI)_{sc}$ from the experimental initial equivalent stiffness of the shear connector, $(EI)_{eq.i}$. By knowing the effective stiffness and Young's modulus of the concrete, the effective thickness of the concrete surrounding the shear connector, t_c can be calculated as shown in Table 3.

Table 3 Initial equivalent stiffness properties

Speci-men	$(EI)_{eq.i}$ kN-mm^2	$(EI)_{con}$ kN-mm^2	E_c N/mm	t_c mm
S-1 *	1.95×10^6	1.62×10^6	23249.29	17.73
S-2 *	7.91×10^6	7.57×10^6	23602.65	29.49
S-3 *	2.13×10^7	2.09×10^7	23602.65	41.40
S-8	1.97×10^6	1.63×10^6	20224.22	18.62
S-9	1.37×10^6	1.04×10^6	21695.84	15.64
S-10	2.38×10^6	2.05×10^6	26593.76	18.32

* : Specimen in Ref. 1) $E_c = 4730\sqrt{f_c'}\ N/mm^2$ [5)]
$(EI)_{sc} = 3.33\times10^5$ kN-mm^2

It can be seen that the effective thickness of the concrete surrounding the shear connector, t_c for specimen S-9 was relatively small among the specimens with the same height of the shear connector. Regarding to this effect, the following equation was proposed to predict the effective thickness of the concrete surrounding the shear connector:

$$t_c = \alpha h_{sc}^{0.675} \quad (t_c \text{ and } h_{sc} \text{ in mm}) \qquad (3)$$

where, α : coefficient for shape effect
(1.51 for L and T shape, 1.29 for I shape, each of which is the average of 12 shear connector)

5.2.2 Q_c value

Q_c is the value of the transferred shear force when a sudden decrease of the equivalent stiffness of the shear connector starts[1]. The Q_c was chosen in such a way that both calculated initial linear stiffness and nonlinear range agree well with the experimental ones as shown in Figs. 13 to 15.

In order to predict more precisely the Q_c values of the specimens in both of this study and the previous study, the formula in the previous study was modified slightly in this study.

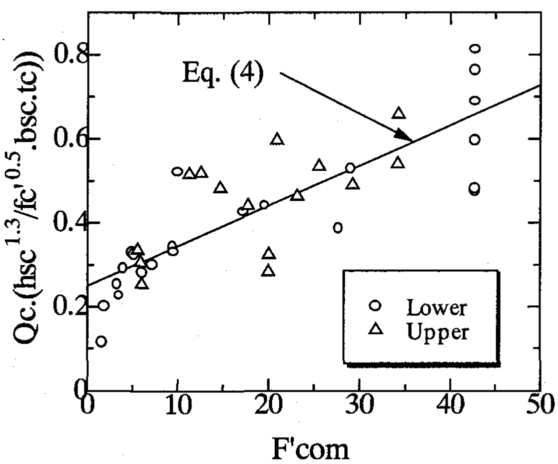

Fig. 10 The relationship between Q_c and corresponding compressive force

Since the Q_c values are not different between the upper and lower cases of the shear connector as shown in Fig. 10, the same formula can be used to predict Q_c for the both cases. The parameters which affect the Q_c value were taken as in the previous study[1]. The vertical axis in Fig.10 shows the Q_c values normalized by its parameters.

The following equation is then introduced to predict the Q_c value.

$$Q_c = \left(0.00955\ F'_{com} + 0.25\right) f'^{1/2}_c \frac{b_{sc}\, t_c}{h^{1.3}_{sc}} \qquad (4)$$

where, F'_{com} : the vertical compressive force of the concrete surrounding the shear connector

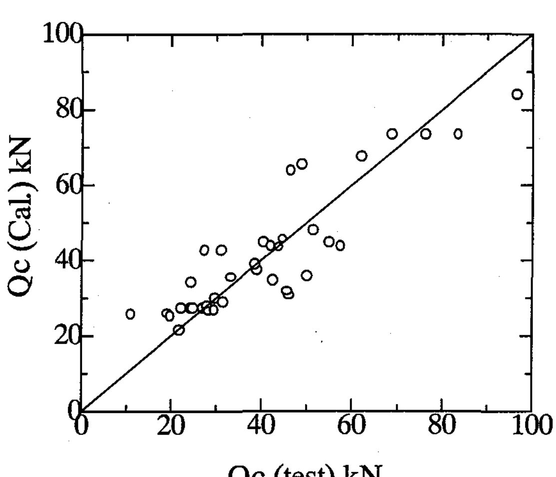

Fig. 11 Comparison between predicted and measured Q_c values

Figure 11 shows the comparison of the predicted Q_c values and the experimental ones. It can be seen that the predicted results are in good agreement with the experimental ones.

The agreement can be seen equally for different concrete strengths as shown in Fig. 12, which indicates the appropriateness of the function, $f'^{1/2}_c$ in the Q_c formula.

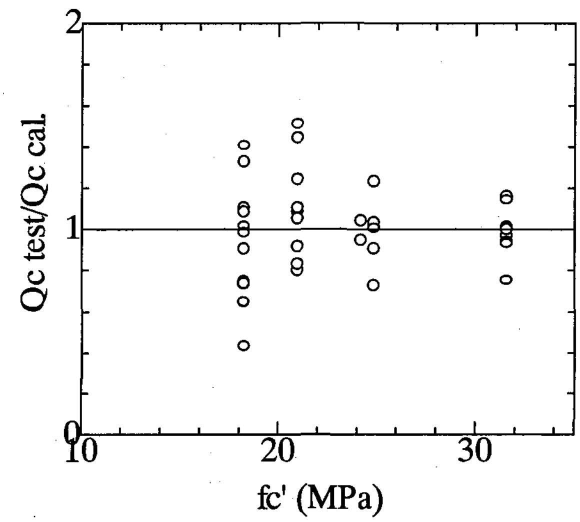

Fig. 12 The relationship between Q_c ratio and concrete strengths

5.2.3 Transferred shear force and relative displacement relationship

The analytical results of the relationship between the transferred shear force and relative displacement for specimens S-8, S-9 and S-10 compared with the experimental ones are shown in Figs. 13, 14 and 15 respectively. Generally good agreement can be seen. The broken lines in the figures indicate the stiffness of the shear connector itself.

As in Ref.1), in the inelastic range, in which the transferred shear force is greater than Q_c, the effective stiffness of the concrete surrounding the shear connector was reduced with an increase in the transferred shear force by a similar function to that of the Bronson's equation for bending stiffness of reinforced concrete beam[5]. It can be seen that the transferred shear forces at a sudden decrease of the equivalent stiffness of the shear connector were different between different specimens. The experimental data of the shear connector SC-3 (RL) in specimen S-8 did not indicate the sudden decrease of the stiffness as shown in Fig. 13.

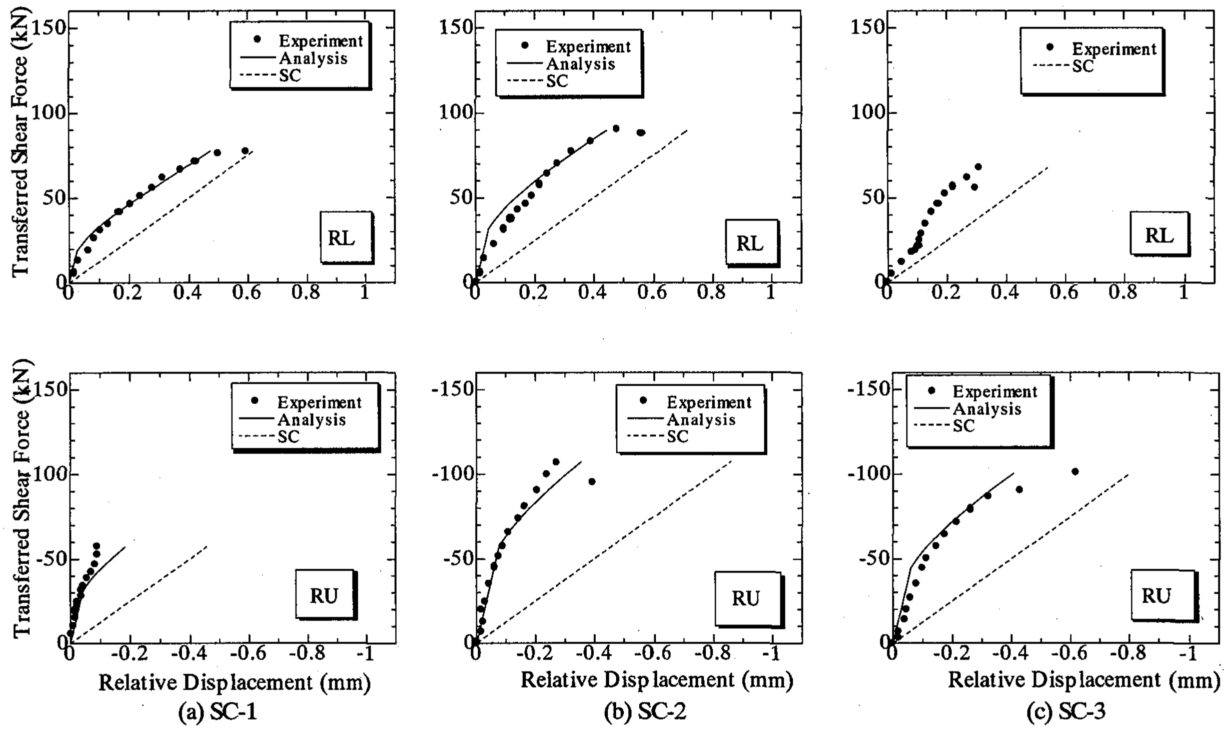

Fig. 13 The experimental and the analytical relationship between transferred shear force and relative displacement in specimen S-8

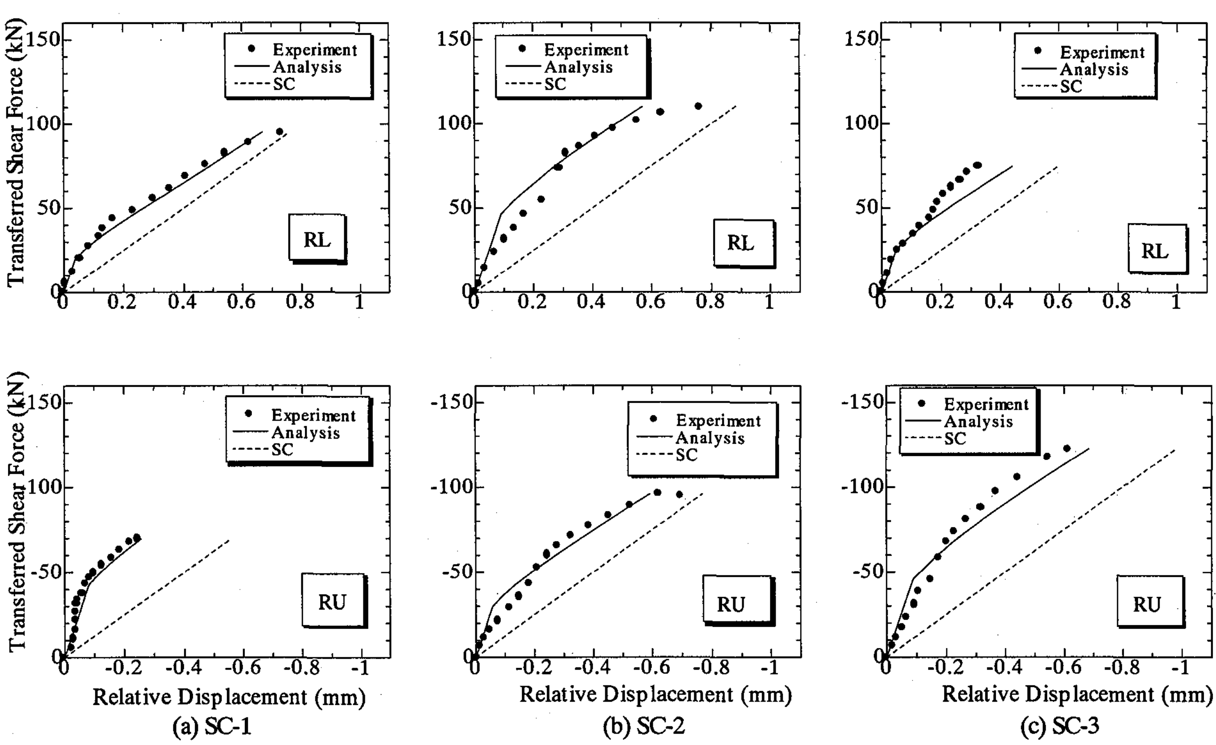

Fig. 14 The experimental and the analytical relationship between transferred shear force and relative displacement in specimen S-9

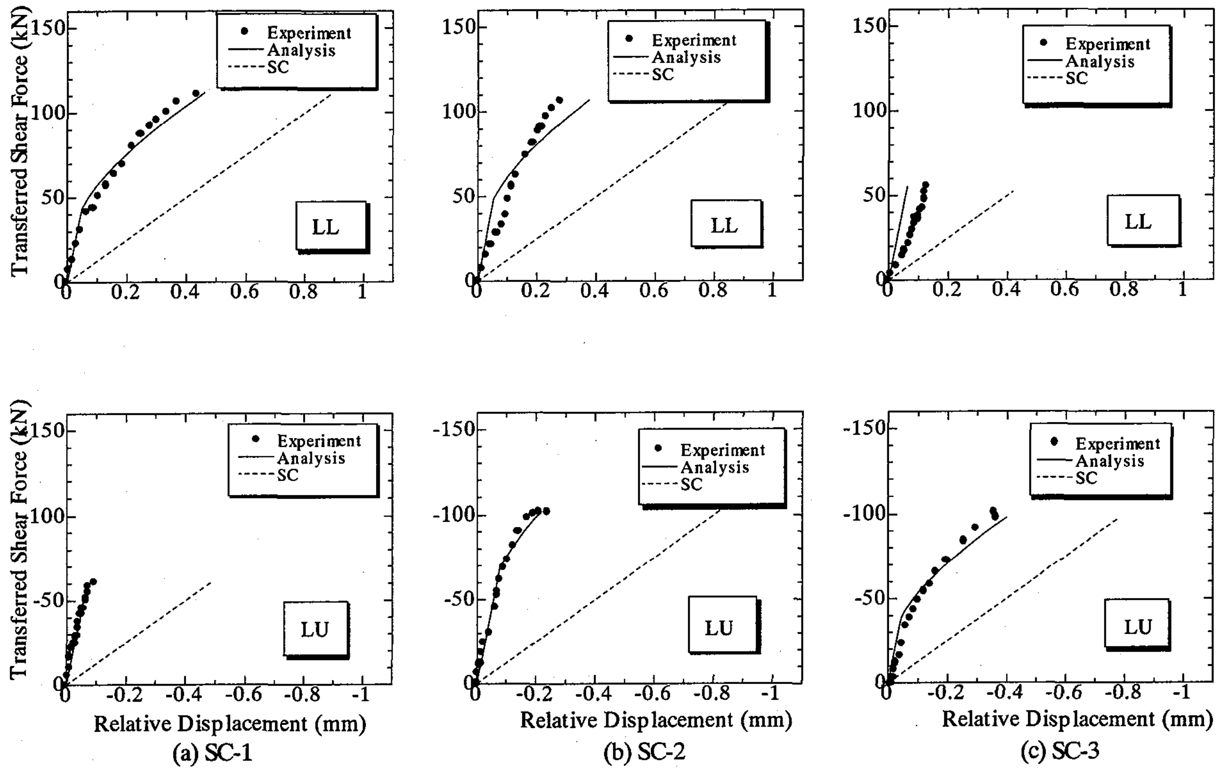

Fig. 15 The experimental and the analytical relationship between transferred shear force and relative displacement in specimen S-10

6 CONCLUSIONS

An experimental investigation was conducted with three steel-concrete sandwich beams. From the investigation on the relationship between the transferred shear force and relative displacement of the shear connector, the following conclusions were derived.

1. The boundary condition, which is no rotation at the top of the shear connector and uniformly distributed load on the shear connector, can be used to analyze the relationship between the transferred shear force and relative displacement of the shape steel shear connector in steel-concrete sandwich beams.
2. A revised formula to predict the effective thickness of the concrete surrounding the shear connector was proposed for the cases of L, T and I shape of the shear connector.
3. A revised model to predict the relationship between the transferred shear force and relative displacement was proposed. The model is applicable for the cases of different compressive strength of concrete and different shape and location of shear connector.

Since these conclusions are derived from test results of a small number of specimens as well as a small size of specimen compared with the actual structure, they should be confirmed with additional study in the future.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Prof. Yoshio Kakuta of Hokkaido University for his comments on this study and to Mr. Tsutomu Kimura and Mr. Yoshinori Matsui of Hokkaido University for their assistance in the experimental works carried out in this study.

REFERENCES

1. Saidi, T., Furuuchi, H., Ueda, T.: Relationship Between Transferred Shear Force and Relative Displacement of Shear Connector In Steel-Concrete Sandwich Beam, Journal of Structural Engineering, Vol. 44 A, March 1998, pp. 1537-1545.
2. Saidi, T., Kimura, T., Furuuchi, H., and Ueda, T.: Effect of The Concrete Compressive Strength on The Shear Connector Behavior For Steel-Concrete Sandwich Beam, Proceedings of Hokkaido Chapter of the JSCE Conference, Vol. 54, February 1998, pp. 686-691.

3. Saidi, T., Furuuchi, H., Ueda, T., and Kimura, T.: Experimental Study on Mechanical Behavior of The Shear Connector For Steel Concrete Sandwich Beam, Proceedings of Hokkaido Chapter of the JSCE Conference, Vol. 53, February 1997, pp. 568-573.
4. JSCE Research Subcommittee on Steel-Concrete Sandwich Structures: Design Code for Steel-Concrete Sandwich Structures - Draft, Concrete Library of JSCE No. 20, pp.1-21, December 1992.
5. P. Park and T. Paulay: Reinforced Concrete Structures, John Wiley and Sons, 1975.

NOTATION

Unless redefined where they appear, the letter symbols adopted for use in this paper are defined and listed below:

b_{sc} : width of the shear connector
E_c : Young's Modulus of concrete
$(EI)_{con}$: initial effective stiffness of the concrete
$(EI)_{eq,i}$: initial equivalent stiffness
$(EI)_{sc}$: stiffness of shear connector itself
f_c' : compressive strength of concrete
F_{com}' : compressive force
h_{sc} : height of the shear connector
k : spring stiffness
M : bending moment
Q_a : transferred shear force
Q_c : transferred shear force when sudden decrease of the equivalent stiffness of the shear connector
y : relative displacement
y' : slopes
α : coefficient for shape effect of the shear connector

(Received September 18, 1998)