STUDY ON JOINT OF PRECAST SLAB-GIRDER APPLIED IN UNBONDED PRESTRESSED CONCRETE SYSTEM

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ABSTRACT :

In reinforce concrete building has a long span and an outer structural frame designed for resisting seismic force, the seismic force of inner structural frame on the building should be transmitted to outer structural frame through a slab diaphragm. In unbonded prestressed concrete systems, the movement of open and shut is a precondition for cyclic seismic load. To solve these problems, mechanical joint of precast slab-girder which transmits in-plane shear force from precast slab to precast girder is necessary. The joint could satisfy required performance was suggested in this research. The structural performance of the joint was investigated experimentally with full scale of slab-girder specimen. In test result, it was confirmed that the shear cotter type of full precast slab accomplished required performance was possessed almost same shear strength with typical reinforced concrete slab.

KEYWORDS: joint of precast slab-girder, cyclical shear load, unbonded prestressed concrete system

1. INTRODUCTION

The pressure connection of precast column and precast girder with steel wire strand is generally applied in unbonded prestressed concrete system. Therefore, the prestressed concrete system has an advantage on construction, repair and disassemble. Additionally, if the prestressed concrete system is adapted to a building, it is possible to concentrate the damage of frame to the joint and realize high structural performance of the frame. In this study, building has the frame of 18mm span with the height of 6 stories and outer structural frame for resisting seismic force is assumed as shown in Fig1.

In the reinforce concrete building has a long span and an outer structural frame designed for seismic force resisting system, the seismic force of inner structural frame on the building should be transmitted to outer structural frame through a slab diaphragm. In the unbonded prestressed concrete systems, the movement of open and shut is a precondition for precast slab-girder joint under the cyclic seismic load. However, the movement is disturbed if the slab concrete mortar is simultaneously poured into a girder form. However, precast slab is generally unified with precast girder in the prestressed concrete system to make a slab diaphragm in the building. Therefore, the joint of precast slab-girder has an effect on structural behavior of frame since the movement of open and shut on the joint of precast slab-girder is disturbed. To solve these problems, mechanical joint of precast slab-girder which transmits in-plane shear force from precast slab to precast girder is necessary. This joint should transmit shear force in girder direction and slide in right-angle direction of girder as shown in Fig. 2.

In this research, the joint of precast slab-girder which could satisfy required performance was suggested and the structural performance of the joint was investigated experimentally with full scale of slab-girder specimen. The prestressed concrete system was adapted to realize a long span has light weight. Moreover precast concrete system is investigated to take an advantage on construction, repair and disassemble.

2. IN-PLANE SHEAR FORCE IN SLAB

Pushover analysis of assumed building shown in Fig.1 is accomplished to confirm shear transfer capacity required in a slab. Elasto-plastic analysis program, CANNY, is utilized in this pushover analysis. The

frame of Y direction is subject to the analysis. The lane of X_1, X_2 and X_3 on the building is only replaced to plane model as shown Fig.3 since the building is symmetric. To suppose a slab diaphragm, each frame was tied up together with a rigid member linked by pin joint. High shear strengths of column and girder were arranged to suppose bending yield mechanism in the girder. Tri-liner model of bending spring is used at the edge of a girder. The spring has 1000kN・m yield strength (M_y), a crack open strength of 1/3 yield strength (M_y) and 0.3 decrement ratio of tangential stiffness after occurrence of crack opening.
The slab self load and live load is designed with 10kN/m^2. In seismic force distribution (A_i), the yield strength is considered so that base shear factor may become 0.25. Bending moment due to long-term load is not considered in this analysis. The distribution of seismic force per one frame is shown in Table 1, and the results of pushover analysis are shown in Fig. 4 and Fig. 5. The relation of story shear force and story drift angle at the story drift angle of 1/200, 1/100, 1/50 is shown in Fig. 4. It was confirmed that the story drift angle of second story and third story were increased ahead rather than the other stories. The story drift angle of first story remained at 1/100 when that of third story reached 1/50. The value of the shear force transmitted to a slab in each story drift angle is shown in Fig. 5 and the direction to outer frame of in-plane shear force is set up positive value. With the increment of story drift angle, the shear force transmitted to outer frame at the top floor is increased. Transmitted shear force became 1137kN at ultimate state, and the value of shear force per one meter of a slab becomes 63kN. Therefore, it is necessary that the joint of slab-girder should resist 63kN per one meter of a slab at the outer frame of assumed building.

3 TEST PLAN

3.1 Specimens

Full scale specimen of precast concrete slab was prepared as shown Fig. 6. The slab based on one span of the building is designed with 1000mm in width and 600mm in length. Total five specimens, three types of joints on full precast concrete slab specimen, one half precast concrete slab specimen, one typical concrete slab specimen, were investigated in this study as shown in Fig. 7. Shear force between a slab and a girder was transmitted by concrete shear cotter or dowel bar in the full precast slab specimen. Shear strength of D19 dowel bar calculated by the code[1)] is as follows.

$$Q_1 = 0.7\sigma_y \cdot a_s = 0.7 \cdot 345 \cdot 287 = 69.3\text{kN} \tag{3.1}$$
$$Q_2 = 0.4\sqrt{(E_c \cdot \sigma_B)} \cdot a_s = 144.1\text{kN} \tag{3.2}$$
$$Q = \min(Q_1, Q_2) = 69.3\text{kN} \tag{3.3}$$

Here, σ_y: yield stress of dowel bar, a_s: section area of dowel bar, E_c: Young's modulus of concrete,
σ_B: compression strength of concrete

The shear strength of a D19 dowel bar becomes about 70kN with the calculation mentioned above and satisfies 63kN required at the joint of precast slab-girder. With arranging two dowel bars per one meter of slab width, 140kN shear force designed in full precast slab specimen can be transmitted.
In Shear Cotter Specimen (S1), reentrant part is initially installed at precast slab, and then concrete mortar is poured inside the reentrant part on the precast girder. Finally, the shear cotter on the girder is prepared with the size of 200mm in width, 200mm in length and 150mm in height. Four D19 dowel bars in the shear cotter are arranged to transfer the shear force. 30mm space between two slabs is installed to allow the displacement of the precast slab to right-angle direction of girder. In three types of full precast slab specimens, 30mm space between two precast slabs is basically installed. The displacement between precast column and precast girder, which has 1000mm depth, becomes 20mm if there is 1/50 story drift angle in the unbonded prestressed joint of precast column and precast girder. Finally, the space of 30mm is decided to satisfy the 1/50 story drift angle.
In Vertical Dowel Bar Specimen (S2), the hole of 90mm in diameter is initially prepared in a precast slab, and

then a dowel bar of D19 anchored in the precast girder is inserted in the hole with a steel sleeve. With grouting the space between the steel sleeve and the precast slab, the dowel bar transfers shear force from the slab to the girder in girder direction and slides in right-angle direction of girder.
In Horizontal Dowel Bar Specimen (S3), a D19 dowel bar with 500mm peach arranged at the edge of a precast slab is inserted in the steel sleeve settled in the upper part of a precast girder. Finally, a concrete mortar of upper part of the precast girder is poured to fix the steel sleeve. Shear force in girder direction is transmitted in terms of contacting the dowel bar with the steel sleeve. However, shear force in right-angle direction of girder is not transmitted since the dowel bar inside the steel sleeve slips in right-angle direction of girder. Additionally, the detail of S3 specimen has an advantage of reducing the story height because the top level of a girder and that of a slab become same.
Half Precast Slab Specimen (S4) and Typical Slab Specimen (S5) are additionally prepared to compare the three types of full precast slab specimens.

3.2 Material Properties
The material properties of steel members and concrete members are shown in Table. 2 and Table. 3.

3.3 Loading Plan
Test setup condition adopted in this study is shown in Fig. 8. The girder of the specimen is fixed in the floor with high tension bolt connection. To keep the slab in parallel to girder, four oil jacks are used at the edge of a slab. With controlling the displacement of a slab by the four oil jacks, there is basically 30mm space always between two slabs in S1, S2 and S3 specimens. The slab of S4 and S5 specimen could be kept in parallel to a girder with controlling axial load by the four oil jacks. There are two oil jacks for cyclic shear load in one side of a slab, therefore four oil jacks for shear load are totally used in one specimen. The cyclic shear loading history of each specimen is shown in Fig. 9. The cyclic shear load is gradually increased by displacement of ±1, 2, 3, 4, 6, 8, 12, 16, 20mm. In case of full precast slab specimens, the space between two slabs is initially set up with 30mm, and then the space is changed to 10mm or 70mm. Only in S3 specimen, the space is changed to 10mm or 50mm. The measuring position of shear displacement of the slab is 500mm far from a center of the girder. In S4 specimen, the shear load of ±100kN, ±200kN, ±270kN to the slab is applied under axial load fixed on 0, +0.5σy and +1.0σy of steel bar arranged in the slab. (Here, σ_y=295N/mm^2). Even though two times of steel bar in the slab of S5 specimen are arranged in comparison with S4 specimen, same axial load and same shear load with S4 specimen are applied due to limit loading capacity of oil jack. Namely, under tension axial load fixed on 0, 0.5σy and 1.0σy of steel bar in the slab, cyclic shear load on the slab is applied in S5 specimen.

4. TEST RESULT

4.1 Failure Mode

In this test, crack open width is recorded at the time of peak shear load. Failure of shear cotter in S1 specimen is shown in Fig. 10 and final crack open patterns of all specimens are shown in Fig. 11.
In S1 specimen, when the shear displacement of 2mm was occurred in the slab, shear crack open and bending crack open were developed and reinforcement bar of a slab around shear cotter started to yield. With the increment of shear displacement, the shear cotter twisted and crack open on the shear cotter grew up. When the shear displacement of the slab reached 12mm, shear strength was decreased and the shear fracture of the shear cotter was occurred finally.
In S2 specimen, when the shear displacement of 2mm was occurred in the slab, vertical dowel bar in the girder yielded with bending mode. There was almost no crack open on the slab and the maximum crack open width was only 0.1mm. The dowel bar finally fractured when the shear displacement of the slab reached 20mm.
In S3 specimen, horizontal dowel bar yielded with bending mode in initial stage as well as S2 specimen. There was almost no crack open on the slab and the maximum crack open width was only 0.06mm.

In S4 specimen, the shear crack open width of 0.1mm was appeared under 270kN shear load with no axial load in the slab. Finally, the slab fractured with cyclic shear load of 200kN under $0.5\sigma_y$ axial load in the slab.
In S5 specimen, the shear crack open width of 0.1mm was appeared under 300kN shear load as well as S4 specimen with no axial load in the slab. Shear crack open width of 0.2mm was finally appeared after peak shear load, which is limit loading capacity of oil jack, with $0.5\sigma_y$ axial tension load in the slab.

4.2 Relationship of Load-displacement and Strength Evaluation

The relationships of shear load-displacement for all specimens are shown in Fig. 13. The calculation methods of shear strength in all specimens are explained below.

4.2.1 Shear Cotter Specimen (S1)

Reinforcement bar around shear cotter on the slab yielded at 2mm shear displacement and shear strength of S1 specimen became ultimate value at 8mm shear displacement. The shear cotter on the girder fractured at 12mm shear displacement and the strength was remarkably decreased. The strength of S1 specimen is calculated as fallows. It is recommended to refer to Fig. 12 when calculating the strength of shear cotter.

$$ {}_sQ_c = \sigma_T \cdot t_s \cdot l_s/2 = 111.7(\mathrm{kN}) \tag{4.1} $$
$$ {}_sQ_y = \sigma_y \cdot A_s = 100.7(\mathrm{kN}) \tag{4.2} $$
$$ {}_cQ_c = Q_{CVS} + Q_{CBS} = 122.0(\mathrm{kN}) \tag{4.3} $$
$$ (\sigma_T = 0.1\sigma_B,\ Q_{CVS} = \sigma_T \cdot A_{CVS},\ Q_{CBS} = \sigma_T \cdot A_{CBS}) $$
$$ {}_cQ_u = 201.0(\mathrm{kN}) \tag{4.4} $$

Here,
${}_sQ_c$: crack opening strength of concrete slab
${}_sQ_y$: yield strength of reinforce bar in slab
${}_cQ_c$: crack opening strength of concrete shear cotter
${}_cQ_u$: ultimate shear strength of concrete shear cotter
Q_D: yield strength of dowel bar in shear cotter
t_s: slab thickness, l_s: slab width, A_s: slab section area,
Q_{CVS}: shear strength of vertical section of shear cotter
Q_{CBS}: shear strength of bottom section of shear cotter
A_{CVS}: vertical section of shear cotter
A_{CBS}: bottom section area of shear cotter

The calculation value is mostly coincided with experiment result.

4.2.2 Vertical Dowel Bar Specimen (S2)

Vertical dowel bar has yielded with bending mode at 2mm shear displacement. After yielding of vertical dowel bar, the shear strength of S2 specimen was not increased at all, and only shear displacement was increased monotonically. The shear strength of S2 specimen became ultimate value at 16mm shear displacement. Bending deformation of dowel bar in the steel sleeve returned in a straight line at 12mm shear displacement. Finally, vertical dowel bar fractured due to cyclic load condition at 20mm shear displacement. Yield strength (Q_y) is calculated by bending yield mode of dowel bar and ultimate strength (Q_u) is calculated by the value of elasto-plastic moment.[2)] The calculation value is mostly coincided with experiment result.

4.2.3 Horizontal Dowel Bar Specimen (S3)

Horizontal dowel bar has yielded with bending mode at 2mm shear displacement as well as S2 specimen. Ultimate strength of S3 specimen was larger than that of S2 specimen. Ultimate strength (Q_u) is calculated by bending yield mode of dowel bar, which has a boundary condition of fixed edge to the slab side and hinge edge to the sleeve side.[2)]

4.2.4 Half Precast Slab Specimen (S4)

Steel bar in the slab started to yield at 270 kN shear load when there is no axial tension load in the slab. When there was $0.5\sigma_y$ axial tension load in the slab, the shear stiffness was decreased. With $0.5\sigma_y$ of axial tension

load in the slab, the slab fractured at 200kN shear load and then shear stiffness was remarkably decreased. Finally, in case of 1.0σ_y of axial tension load in the slab, the shear strength was not increased at all.
Q_c and Q_s were calculated by the shear strength equation of wall structure [3), 4)]. The slab section area for Q_c is obtained from 100mm thickness and 1000mm width. The crack opening due to axial tension load in the slab is the reason why the slab strength could not be reached the ultimate strength (Q_s).

$$Q_c = \tau_{scr} \cdot t_s \cdot l_s / \chi_s \quad (4.5)$$
$$\tau_{scr} = \sqrt{(\sigma_T^2 + \sigma_0 \sigma_{0T})} \quad (4.6)$$
$$Q_c = 211\text{kN (in } \sigma_0 = 0\text{)},\ Q_c = 137\text{kN (in } \sigma_0 = -1.87\text{)}$$
$$Q_s = p_s \cdot \sigma_{sy} \cdot t_s \cdot l_s = 453\text{kN} \quad (4.7)$$

4.2.5 Typical Slab Specimen (S5)
The steel bar in the slab has yielded at 300kN shear load under 0.25σ_y axial tension load in the slab. Nevertheless, the shear strength and shear stiffness of S5 specimen were not decreased. The specimen has not fractured under 300kN shear load, which is limit loading capacity of oil jack. Q_c and Q_s is calculated as well as S4 specimen.

4.3 Stiffness and Strength
When there is 30mm space between two slabs in S1, S2 and S3 specimen and no tension load in S4 and S5 specimen, the relation of shear load-displacement is shown in Fig. 14. The value of q (63kN) means target shear strength per one meter of a slab. The shear strength of S1 specimen reached the target shear strength (63kN) of slab diaphragm at about 1.0mm shear displacement. 2mm displacement on the joint of slab-girder means that the story drift angle on the top story becomes 1/2000 calculated from 4m story height. There is less influence of 1/2000 story drift on the frame because the safety limitation of story drift angle is 1/50. With seismic load condition of 70mm space in S1 and S2 specimen, 50mm space in S3 specimen and 187kN axial tension load in S4 and S5 specimen, it was confirmed that shear stiffness and strength of S1 specimen were almost same with those of S4 specimen as shown in Fig. 15.

5. CONCLUSION
The results of experimental study on joint of precast slab-girder applied in prestressed concrete system are as follows.

- The shear cotter type of full precast slab accomplished required performance is possessed almost same shear strength with typical reinforced concrete slab.
- The calculation values of shear stiffness and shear strength in every specimen were properly appraised in comparison with the results of experiment.

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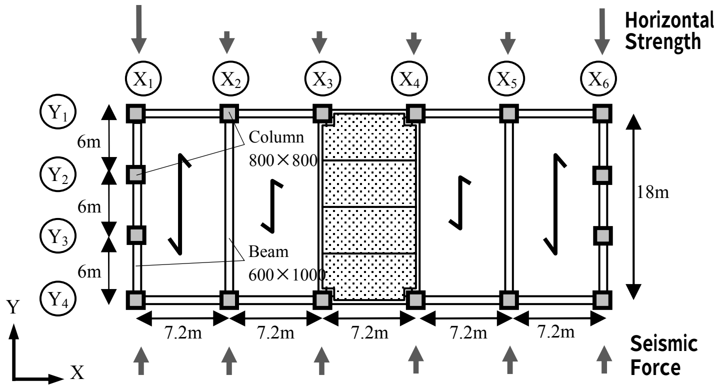


Fig.1 Assumed Building Plane

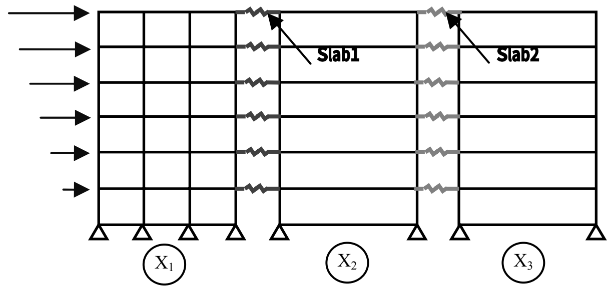


Fig.3 Modeling of Slab

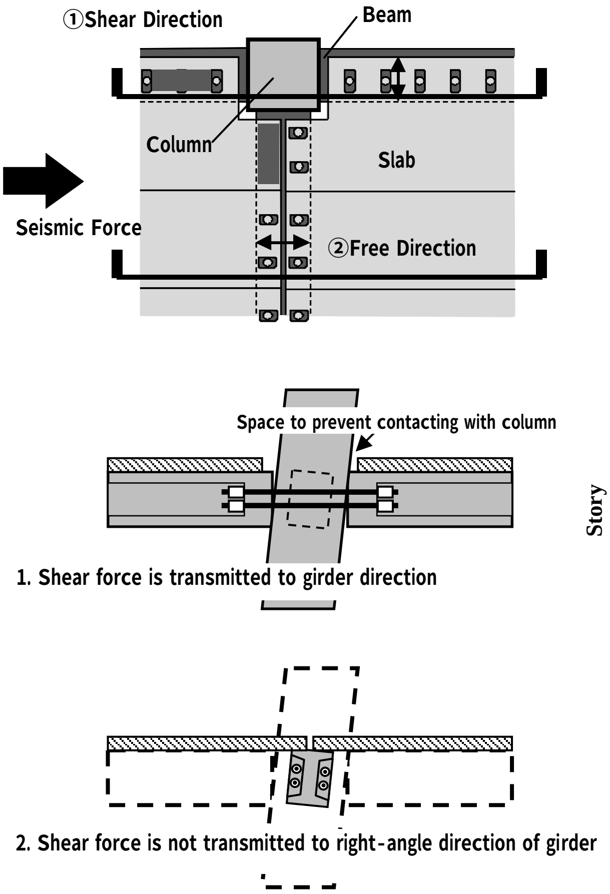


Fig.2 Joint of Precast Slab-Girder

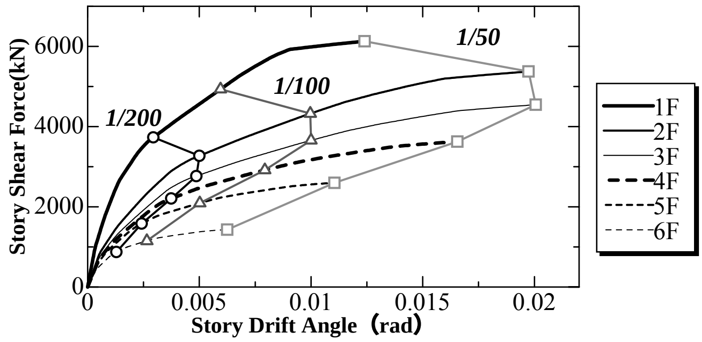


Fig.4 Result of Pushover Analysis

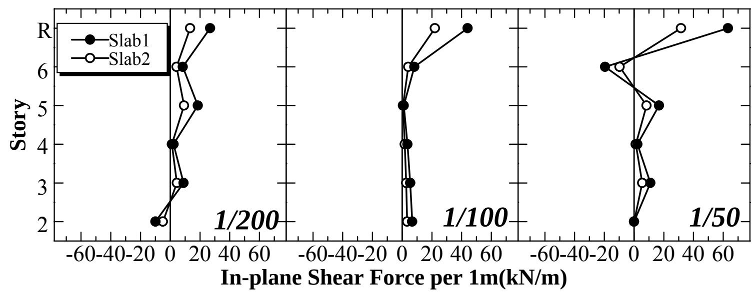


Fig.5 In-plane Shear Force

Table.1 Seismic Force per One Frame

Story	Height (m)	Weight (kN)	∑Wi (kN)	Ai	Ci	Qi (kN)	Pi (kN)
6	4.0	1296	1296	1.90	0.47	615	615
5	4.0	1296	2592	1.55	0.39	1005	390
4	4.0	1296	3888	1.36	0.34	1322	317
3	4.0	1296	5184	1.22	0.30	1581	259
2	4.0	1296	6480	1.10	0.28	1787	206
1	4.0	1296	7776	1.00	0.25	1944	157

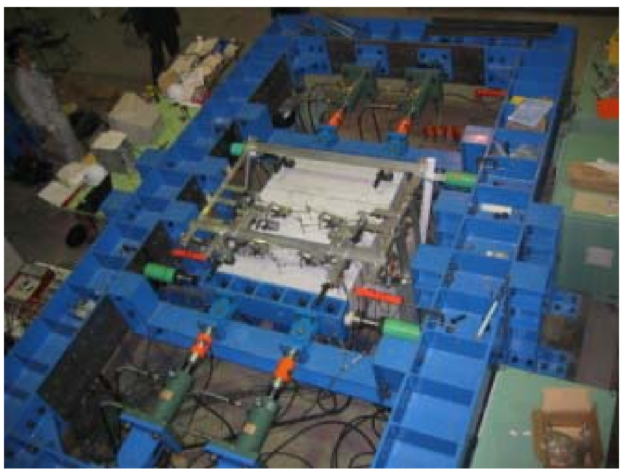
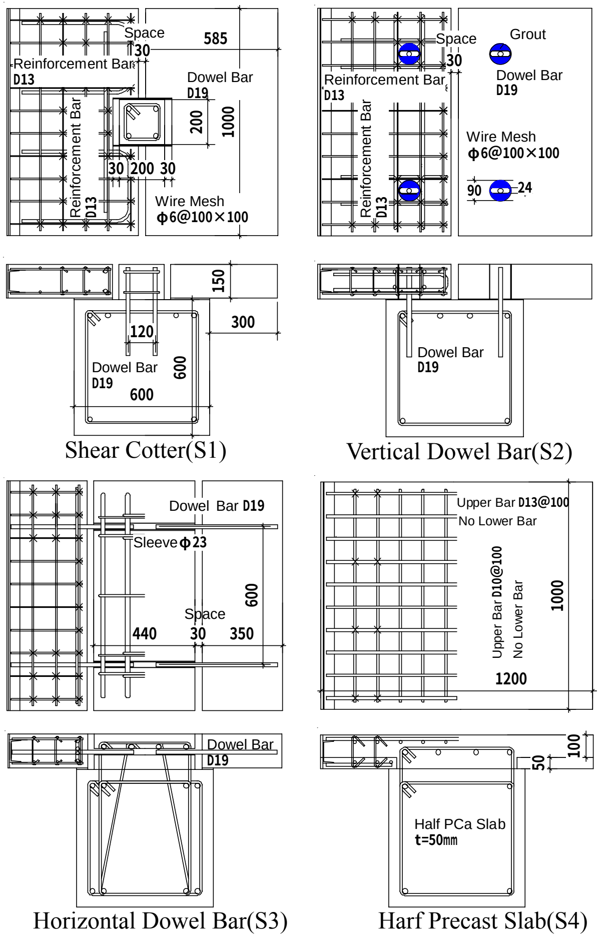


Fig.6 Precast Concrete Slab



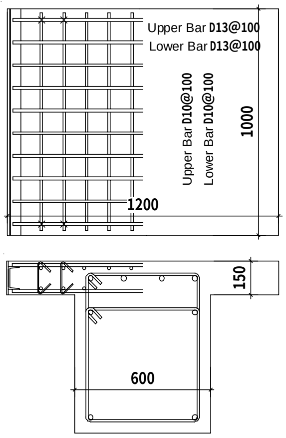


Fig.7 Slab Specimens

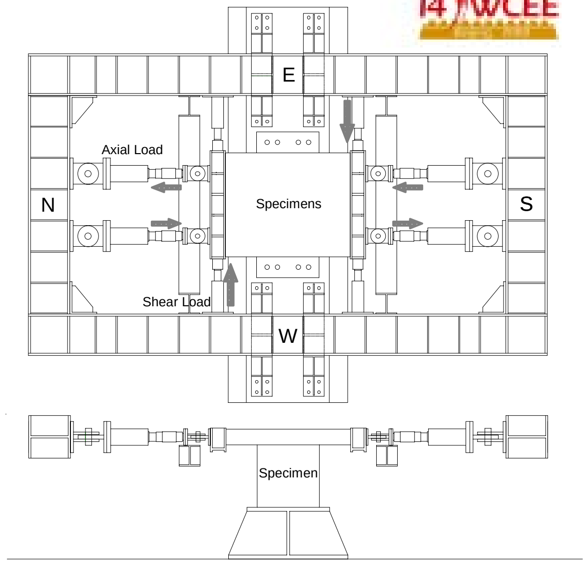
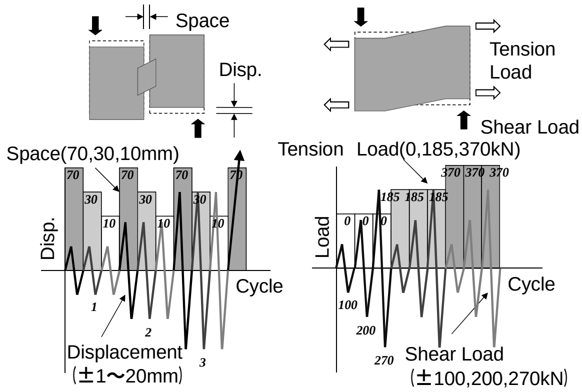


Fig.8 Test Setup Condition



Full PCa Slab(S1〜S3) Conventional Slab(S4,S5)

Fig.9 Cyclic Shear Loading History

Fig.10 Failure of Shear Cotter (S1)

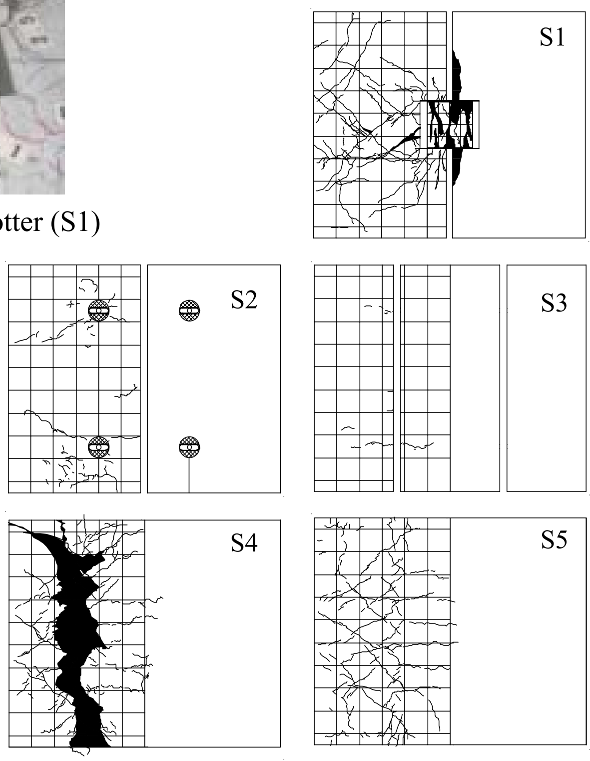


Fig.11 Final Clack Open Pattern

Table.2 Materials Properties of Steel Members

Steel	σ_y (MPa)	σ_u (MPa)	E_s (GPa)	Usage
D10	373.2	506.7	170	Slab Bar
D13	356.3	511.0	166	Slab Bar・Rein.Bar
D19	396.5	563.2	174	Dowel Bar

Table.3 Material Properties of Concrete Members

	σ_B (MPa)	E_c (GPa)	day	σ_T (MPa)	Note
Concrete	52.4	24.4	68	3.0	Former
Concrete	52.2	25.0	88	3.2	Latter
Grout	64.9	23.9	109	3.1	

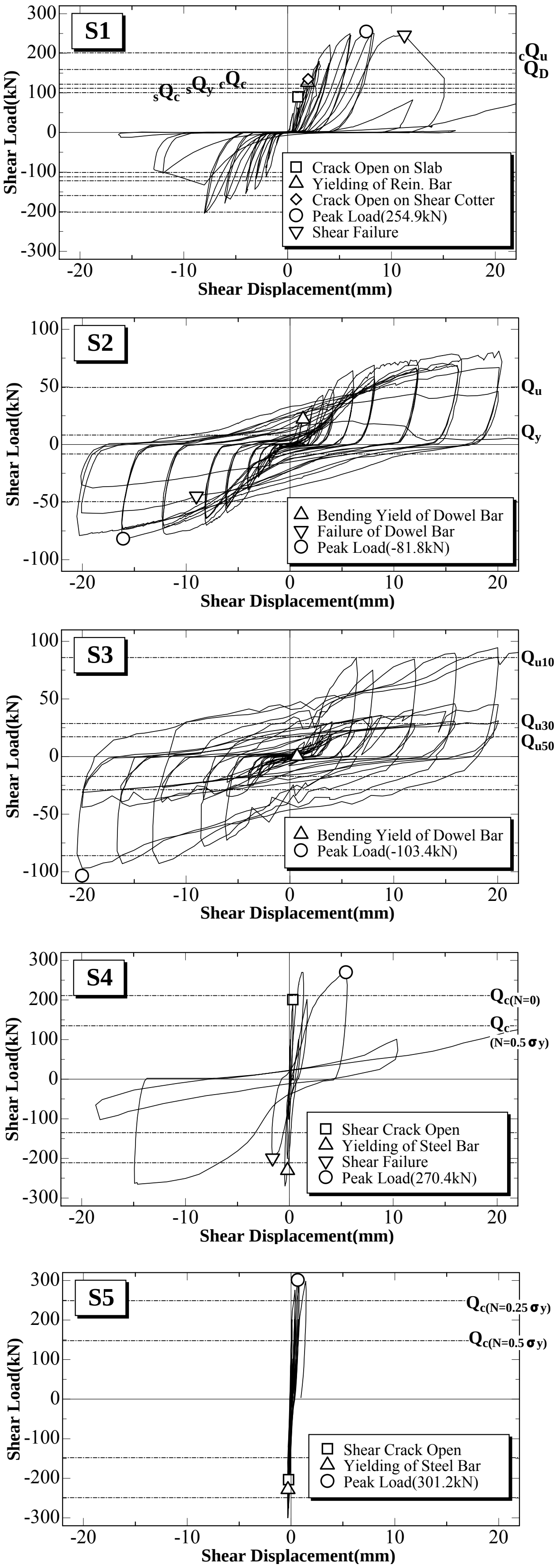


Fig.13 Relationship of Shear Load-Shear Displacement

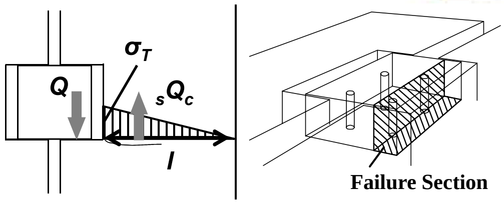


Fig.12 Summary of Calculation (S1)

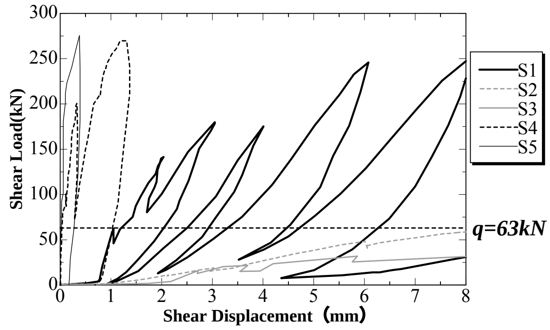


Fig.14 Test Results under no axial load in slab

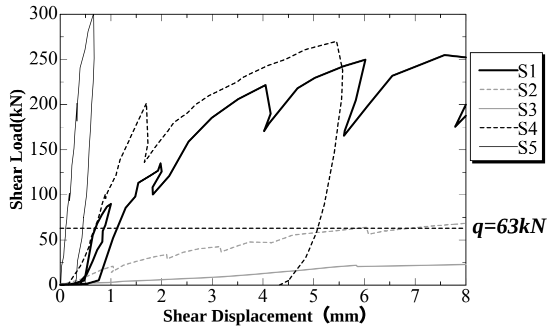


Fig.15 Test Results under axial load in slab