16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 621

Registration Code: S-H1462602927

An experimental study on seismic performance and failure mode at the end of RC beams with non-structural wall having structural gaps

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Abstract

Currently, RC structure including beams with secondary walls and influences of these walls are ignored in Japan, because they are considered as non-structural elements having structural gaps. However, there were few adequate studies on the seismic behavior of these members. Additionally, it has been pointed out that beams with low shear margin have possibility to cause shear failure. In this research, static loading tests were conducted to investigate seismic behavior of beams with non-structural walls having structural gap. Six beams with different parameters were investigated as the following. Two beams: a beam with shear margin of near 1.1, one beam: spacing between stirrups in hinge regions was decreased, three beams: with slab and their walls are as spandrel or hanging wall. The experimental results were as the followings. For two beams with wall simply, after yielding of main bars, shear failure with fracturing of stirrups occurred. For four beams, spacing between stirrups was decreased and with slabs, were able to finish the tests without shear failure. As the test results, the beam with non-structural wall having structural gaps had the possibility of shear failure occurred, even in the beam having more than 1.1 of shear margin. Moreover, it was found that it was possible to prevent shear failure by increasing the end reinforcement and effect of the slab restraint.

Keywords: RC beam, shear failure, non-structural wall, structural gap

1. Introduction

Currently, RC structures including beams with secondary walls and influences of these walls are ignored in Japan, because they are considered as non-structural elements. The non-structural walls have structural gaps at end of them in order to avoid shortening the height of side columns. However, there were few adequate studies on the seismic behavior of these members. Additionally, it has been pointed out that beams with low shear margin have possibility to cause shear failure. According to previous researches[1)], even though it had a high shear margin as about 3.8, stirrups yielded. From this, there may be possibility of shear failure if an element had a low shear margin. Therefore, in this research, static loading tests were conducted to investigate seismic behavior of beams with non-structural walls having structural gap having a low shear margin.

2. Experimental cutline of experiment

2.1 Outlines of specimens

The parameters of specimens are shown in Table 1, the material properties are shown in Table 2 and Table 3, and the detail reinforcement of specimens are illustrated in Fig. 1.

Table 1 – properties of test specimens

specimen	SP-S5	SP-S5+slabT	SP-S6	SP-S6+AR	SP-S6+slabT	SP-S6+slabK
beam width(mm)	200					
beam height(mm)	300		400			
beam main bars	2-D19	2-D16	3-D19		2-D19+D10	
pt	1.10%	0.76%	1.20%		0.89%	
beam stirrups	2-D4@70	2-D6@100	2-D6@50	2-D6@50 hinge zone@35	2-D6@40	
pw	0.20%	0.32%	0.64%		0.79%	
wall width(mm)	80					
wall height(mm)	350					
gap width(mm)	15		25			
wall horizontal bars	2-D4@150					
wall vertical bars	2-D4@150					
wall end bars	4-D6					
slab width(mm)	–	500	–		500	–
slab thickness(mm)	–	100	–		100	–
Concrete design strength(N/mm^2)	24					
beam span(mm)	1700					
shear margin	1.30	1.21	1.32	1.32	1.24	1.19

Table 2 – Mechanical Properties of Reinforcement Bars

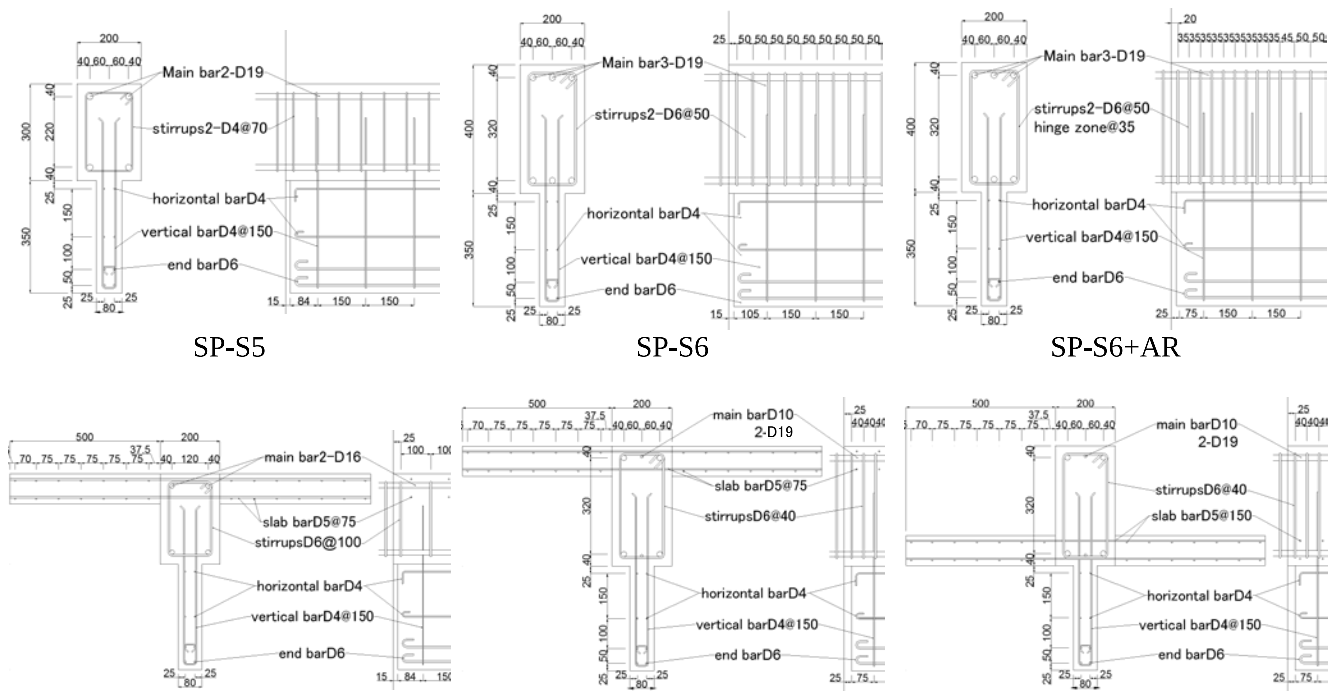
	steel bar													
specimen	SP-S5/SP-S6			SP-S6+AR/SP-S6+slabT					SP-S5+slabT/SP-S5+slabK					
type	D4	D6	D19	D4	D5	D6	D10	D19	D4	D5	D6	D10	D16	D19
young modulus $\times 10^5$(N/mm^2)	1.83	1.9	1.96	1.67	1.87	1.96	1.91	1.92	1.79	2.04	1.94	1.77	1.79	1.68
yielding strength (N/mm^2)	356.4※	433.2	383.6	398.2	371.0※	374.1※	367.1	380.1	397.7※	374.2※	361.6※	390.7※	366.6	390.0
yielding strain(%)	0.43	0.24	0.21	0.23	0.39	0.37	0.22	0.23	0.41	0.39	0.37	0.32	0.21	0.23
tensile strength (N/mm^2)	523.8	533.3	563.9	484.4	410.4	515.6	515.6	549.4	543.8	542.6	525.4	542.5	556.4	582.6

※mark represents 0.2% offset strength.

Table 3 – material properties of concrete

	concrete					
specimen	SP-S5	SP-S6	SP-S6+AR	SP-S6+slabT	SP-S5+slabT	SP-S6+slabK
compression strength (N/mm^2)	27.6	28.2	27.7	27.4	31.1	31.3
conpression strain(%)	0.21	0.23	0.21	0.22	0.19	0.20
young modulus $\times 10^4(N/mm^2)$	2.3	2.27	2.24	2.2	2.53	2.55
split tensile strength (N/mm^2)	2.50	2.39	2.39	2.16	2.80	2.60

Young modulus of concrete was slope connecting the 1/3 and the origin of the maximum compressive strength.



SP-S5 SP-S6 SP-S6+AR

SP-S5+slabT SP-S6+slabT SP-S6+slabK

Fig. 1 – Geometry and Reinforcement Details

Total six specimens were prepared, i.e.; SP-S5: a beam with shear margin 1.3, SP-S6: a beam with shear margin 1.3 and high shear stress of flexural yielding, SP-S6+AR: a beam SP-S6 strengthened against shear failure by increasing the stirrups in the hinge zones of end, SP-S6+slabT: a beam SP-S6 with slab as the wall is hanging wall, SP-S6+slabK: a beam SP-S6 with slab as the wall is spandrel wall, and SP-S5+slabT: a beam SP-S5 with slab as the wall is hanging wall. All specimens were designed their shear margin of 1.1 as the target. The shear margin is defined as shear strength divided by flexural strength ignoring the wall. Flexural strength of three specimens with slab was defined as the average value during compression and tension slab. Shear strength was calculated ignoring the slab bars.

2.2 Measuring method

The strain was measured by the strain gauges attached on steel bars in the specimens. Load measured by the load cell attached at the end of jack. Moreover, the crack width was measured using a crack scale. Displacement transducers were fixed on the back of specimen.

2.3 Loading protocol and Test setup

The test setup and loading protocol were illustrated in Fig. 2 and Fig. 3, respectively.

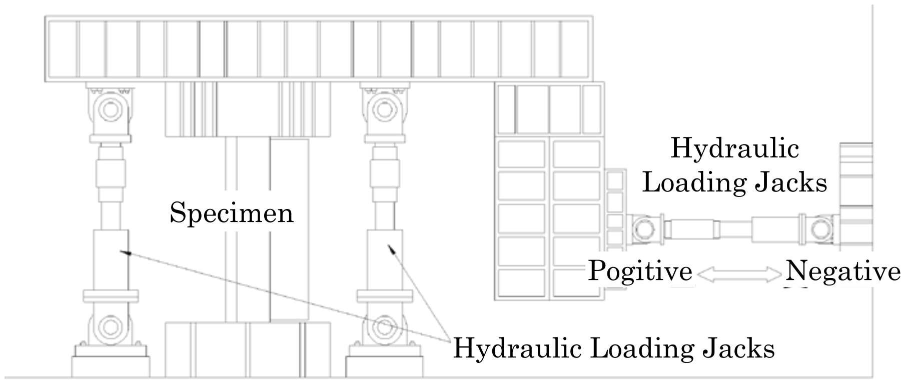


Fig. 2 – Loading Apparatus

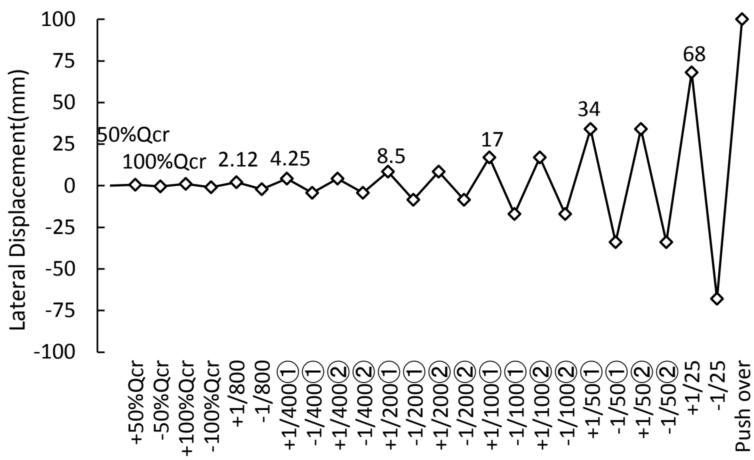


Fig. 3 – Loading Protocol

The studied beams were placed vertically and were applied to lateral displacement at the upper surface of the upper support. The horizontal load was measured depending on the applied lateral displacement corresponded with the loading protocol shown in Fig.3. In general, the loading protocol was as the following: 50% of Q_{cr} and 100% of Q_{cr} once, ±1/800, ±1/400, ±1/200, ±1/100 and ±1/50 twice and ±1/25 once then continuing the loading until fracture toward the positive loading direction.

Cracking strength of specimen is calculated by Eq. 1:

$$Q_{cr} = 0.56\sqrt{\sigma_B} \cdot Z_e /(l/2) \tag{1}$$

Where: Q_{cr}: concrete cracking strength of concrete (N/mm^2). σ_B: compressive strength of concrete (N/mm^2). Z_e: section shape factor, taking into consideration the rebar. L: length of beam (mm).

Four hydraulic oil jacks, two vertical jacks and two horizontal jacks, were used. The two vertical jacks were used to keep the upper support horizontal and axial force is controlled to be zero. The horizontal jack was used to apply the lateral displacement.

3. Experimental Results

3.1 *Q*-*δ* relationship

The relationships between shear force and displacement of all specimens and red continuous lines representing tri linear model, whose calculation will be described in following section 3.3 are shown in Fig. 4.

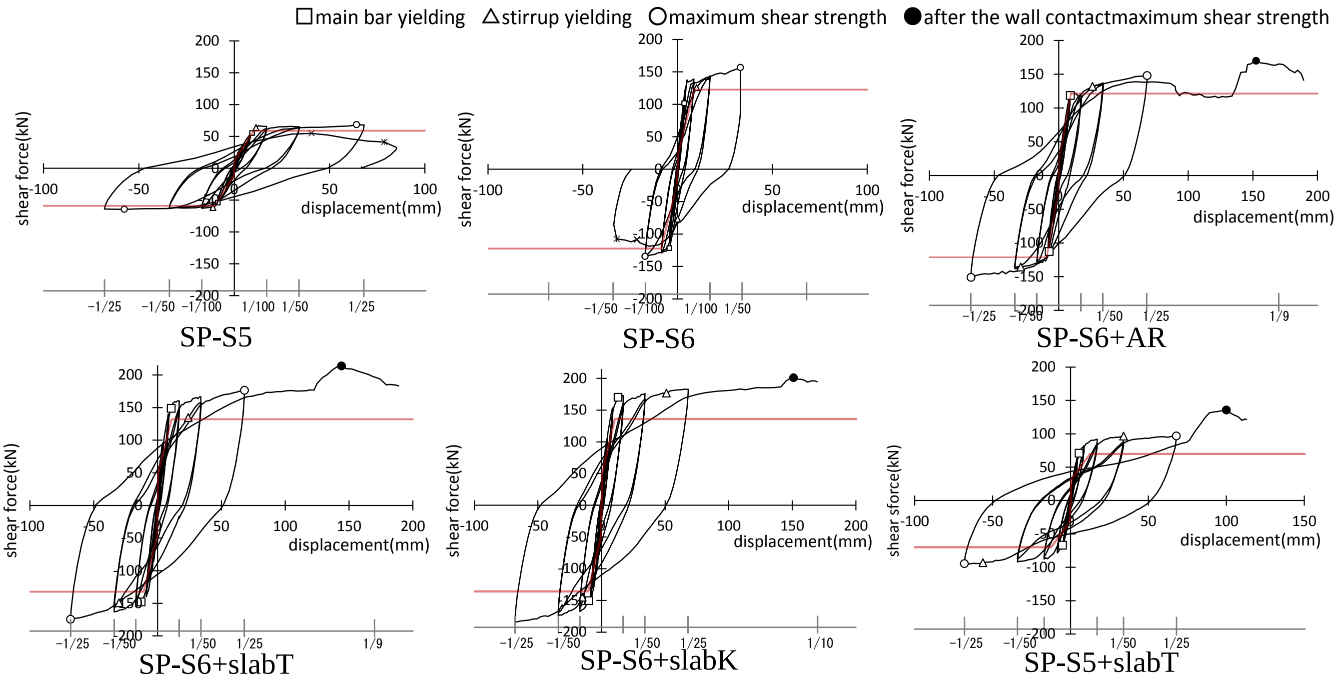


Fig. 4 – *Q*-*δ* relationship

For the specimen SP-S5, the stirrups yielded before main bars yielding at the drift angle R=1/100(rad.) in both positive and negative direction. Thereafter maximum shear force was recorded in R=1/25(rad.). However, at the middle second cycle of R=+1/25(rad.), shear force decreased and a stirrup was fractured near R=+1/28(rad.), so the loading was finished.

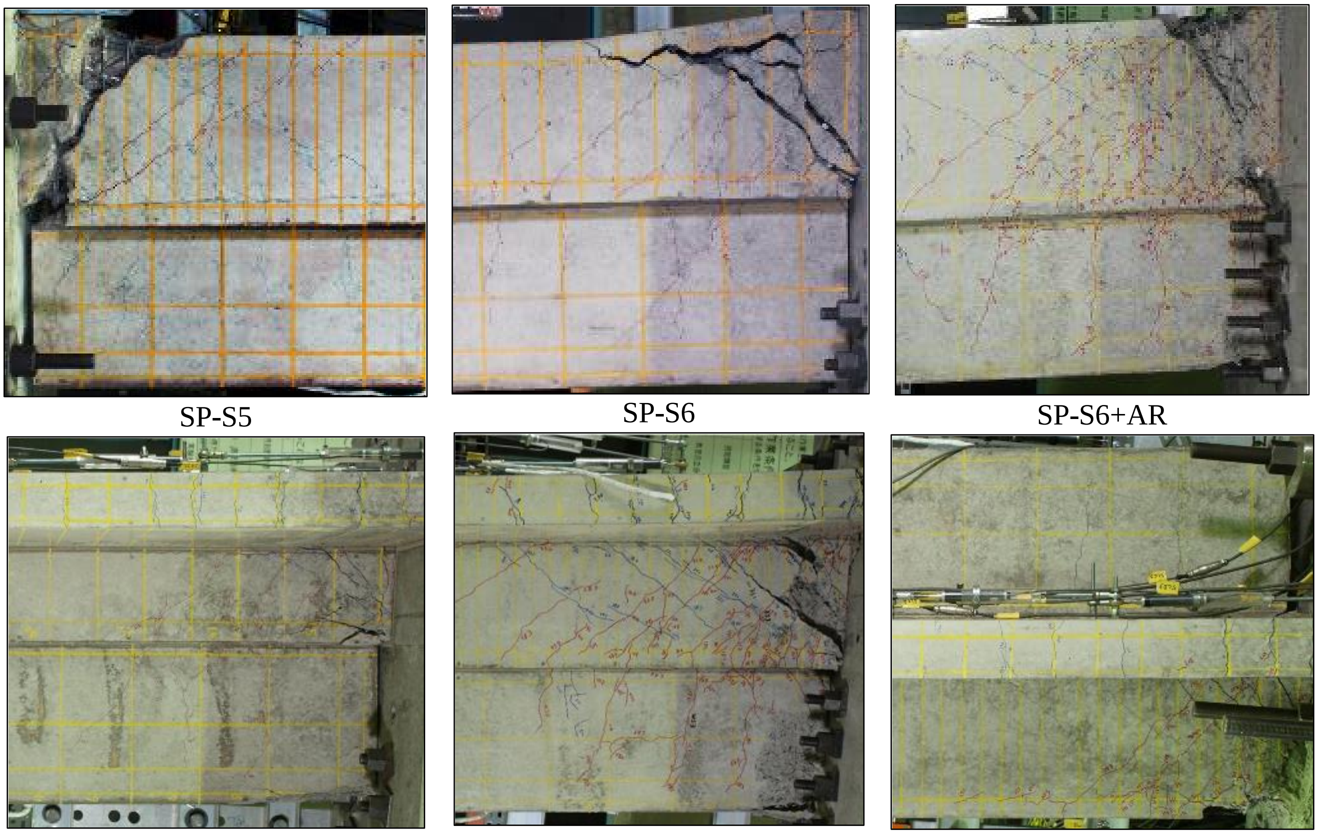
For the specimen SP-S6, the main bar yielded in the cycle of R=±1/200(rad.) for in positive and negative direction. And the stirrups yielded on R=+1/50 and -1/100(rad.). Also, each was recorded the maximum shear strength at the peak of the cycle, respectively. However, at the middle first cycle of R=-1/50(rad.), shear force decreased and a stirrup fractured near R=+1/28(rad.), so the loading was finished.

For the specimen SP-S6+AR, SP-S6+slabT, SP-S6+slabK, SP-S5+slabT, stirrups yielded after the main bars yielded. On SP-S6+AR, the stirrups were surrendered in the R=1/50(rad.) cycle in the positive and negative both. On SP-S6+slabT and SP-S5+slabT, the stirrups yielded at R=+1/50 and -1/25(rad.) cycle. On SP-S6+slabK, the stirrups yielded at R=+1/25 and -1/50(rad.) cycle respectively. Moreover, all of 4 specimens recorded maximum force at R=±1/25(rad.) cycle. In addition, at any of the four specimens, stirrups were not broken. The loadings were finished at R=+1/9(rad.) for specimen SP-S6+AR and SP-S6+slabT, and at R=+1/10 and +1/15(rad.) for SP-S6+slabK and SP-S5+slabT, respectively. For all four specimens, shear failure was prevented.

3.2 Destruction situation

The final destruction situations of the end of each specimen are shown in Fig. 5. Incidentally, since a similar behaviors were observed in both beam ends, one end only is shown.

For the specimens SP-S5, SP-S6, shear cracks extending from the structural gap were widely opened, leading to stirrups fracturing and shear failure. For the specimen SP-S6+AR, influence on the cracking angle by the end reinforcement was not observed. In other three specimens with slabs: buckling of the beam main bars or expand of shear cracks were prevented by the slab.



SP-S5 SP-S6 SP-S6+AR

SP-S5+slabT SP-S6+slabT SP-S6+slabK

Fig. 5 – final destruction situations

3.3 Comparison with the previous equations

The experimental values and the calculated values of initial stiffness, flexural crack strength, flexural yielding strength, and yielding deformation angle are shown in Table 4. All of them were calculated ignoring walls. The four calculation methods are shown below.

(1) initial stiffness K_0

Initial stiffness K_0 of the relationship between shear force and displacement was calculated taking into account the bending and shear deformation.

(2) flexural crack strength Q_{cr}

Flexural crack strength is a value obtained by dividing bending cracking moment M_{cr} from Eq. 1 by span as shown in Eq. 1.

(3) flexural yielding strength Q_y

Flexural yielding strength is obtained by dividing flexural yielding moment M_y[2)] by span.

(4) yielding deformation angle R_y

Yielding deformation angle R_y was calculated using the stiffness reduction ratio from the equation proposed by Sugano[2)]

For the specimens with slab, it took the average between tension and compression on slab. When the slab is in compression, the stiffness reduction ratio is calculated as a rectangular beam consisting of a slab full width and beam height. When the slab is in tension, the stiffness reduction ratio is calclated as a rectangular beam consisting of a beam height and width, and is reduced by multiplying the inertia moment ratio of rectanglar beam to Tshape beam.

Table 4 – the experimental values and the calculated values

result		SP-S5	SP-S6	SP-S6+AR	SP-S6+slabT	SP-S6+slabK	SP-S5+slabT
initial stiffness (kN/mm)	experimental	24.5	67.6	32.3	48.8	36.5	23.7
	calculated	22.8	50.4	47.0	86.2	96.5	53.5
	(exp./cal.)	(0.93)	(0.75)	(1.45)	(1.76)	(2.64)	(2.26)
flexural crack strength (kN)	experimental	10.9	30.3	29.4	45.3	64.1	27.2
	calculated	12.7	24.2	23.8	57.6	59.6	38.2
	(exp./cal.)	(1.17)	(0.80)	(0.81)	(1.27)	(0.93)	(1.40)
flexural yielding strength (kN)	experimental	61.4	115.0	111.5	146.5	161.3	80.6
	calculated	58.9	122.5	121.3	132.1	135.9	69.8
	(exp./cal.)	(0.96)	(1.07)	(1.09)	(0.90)	(0.84)	(0.87)
yielding deformation angle (rad.)	experimental	0.70	0.25	0.50	0.37	0.63	0.34
	calculated	0.60	0.51	0.55	0.51	0.49	0.54
	(exp./cal.)	(0.86)	(2.04)	(1.10)	(1.36)	(0.77)	(1.60)

Initial stiffness evaluation accuracy was not high. Flexural crack strengths were the evaluation range of 80 to 140%. Calculation of flexural yielding strength corresponded well to the experiment within ±10% accuracy. Yielding deformation angles of SP-S6+slabK and SP-S5 were underestimated, while for the other specimens, they were overestimated, in particular more than twice for SP-S6.

Although the evaluation method of stiffness need to be improved, the evaluation formula of strength are applicable.

4. Discussion of shear strength

4.1 Effect of the additional reinforcement: SP-S6+AR

Fig. 6 and Eq. 2 show the determination method for the amount of additional reinforcement for SP-S6+AR.

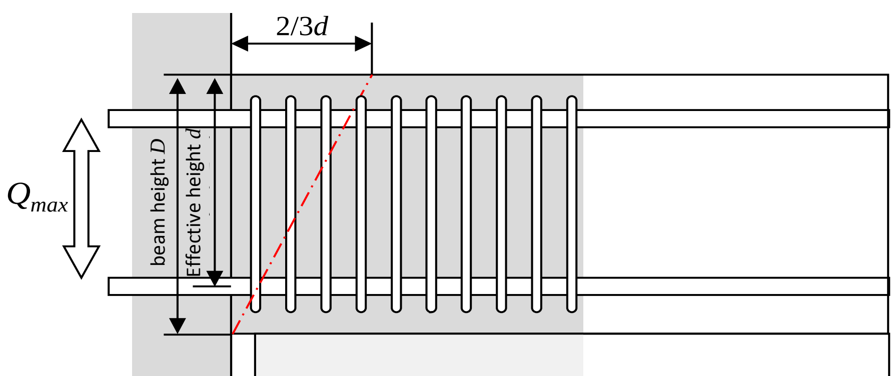


Fig. 6 – end reinforcement

From the experimental result of the SP-S6, Q_{max} was designed as almost exceeding Q_u.

Q_{max} is the capacity of stirrups that are included in the area which was 2/3 of effective depth considered to be effective to shear crack. Q_u is the maximum shear strength recorded in SP-S6 experiment.

$$Q_u < Q_{\max} = \sum a_w \cdot \sigma_y \tag{2}$$

Where, Σa_w: sum of cross-sectional area of stirrups included in the area from the end to 2/3d (mm^2), σ_y: yielding strength of stirrups (N/mm^2).

The results are shown in Table 5. The number of stirrups in the table is the number of reinforcement across the shear crack. In SP-S6+AR, the influence to the crack angle by increasing the end reinforcement was not observed. Because of increasing the stirrups, Q_{max} increased as almost the same of the maximum strength. As a result, it is considered that was able to prevent the shear failure.

Table 5 – comparison of Q_u and Q_{max}

specimen	number of stirrups	beam maximum value (exp.)Q_u	Q_{max} ($a_w \times \sigma_{wy}$)	relation	Failure type
SP-S5	4	66.37	40.06	$Q_{max} < Q_u$	shear
SP-S6	4	145.7	111.0	$Q_{max} < Q_u$	shear
SP-S6+AR	6	149.0	142.2	$Q_{max} \fallingdotseq Q_u$	flexural

4.2 Effect of the slab: SP-S6+slabT, SP-S6+slabK, SP-S5+slabT

The truss-arch theory[3)] is possible to use for shear strength transmission method of beams. Because these specimens were not subject to axial force, it was assumed that the shear force was transmitted by only truss action. The shear resistance was considered as following. Shear strength by truss theory, using the value of the strain of main bars, can be represented as Eq. 3.

$$V_t = a_t E_s \frac{\Delta\varepsilon_t}{\Delta L} j_e \tag{3}$$

Where: a_t: sum of cross-sectional area of beam main bars (mm^2), E_s: Young's modulus of main bars (N/mm^2), $\Delta\varepsilon_t$: main bars strain increment of main bar strain between two gauges (%), ΔL: the distance between the strain gauges (mm), j_e: stress center-to-center distance (mm)

Fig. 7 and Fig. 8 show the comparisons of SP-S6+AR and SP-S6+slabT respectively.

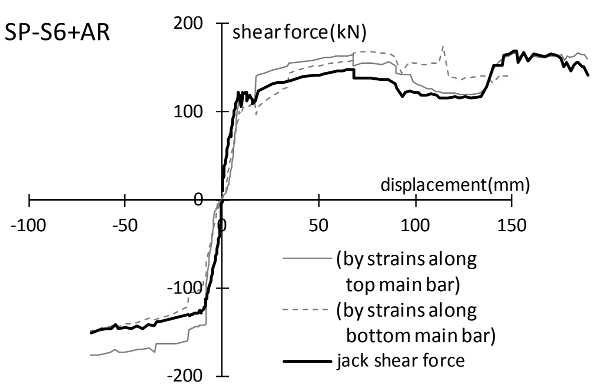


Fig. 7 – V_t comparison (SP-S6+AR)

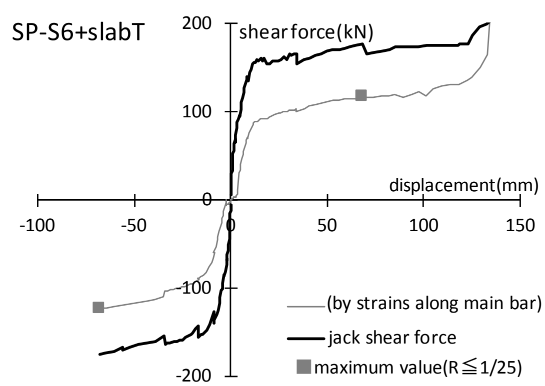


Fig. 8 – V_t comparison (SP-S6+slabT)

For the specimen SP-S6+AR, without slab, estimated value V_t had good agreement with the shear force from the jack. For the specimen SP-S6+slabT, with slab, estimated values from the strain gauges were less than shear force from jacks. The differences between them could be regarded as a part of shear capacities that were carried by slabs. Table 6 shows beam capacity Q_{max} and estimated value Q_u, which was the maximum value in the rotation angle of lower than 1/25(rad.) for each specimen with slab.

Table 6 – comparison of Q_u and Q_{max}

specimen	number of stirrups	beam maximum value (exp.)Q_u	Q_{max} ($a_w \times \sigma_{wy}$)	relation	Failure type
S6+slabT	6	119.7	142.2	$Q_{max} > Q_u$	flexural
S6+slabK	6	105.1	140.6	$Q_{max} > Q_u$	flexural
S5+slabT	2	47.21	46.87	$Q_{max} \fallingdotseq Q_u$	flexural

For each specimen, beam capacity Q_{max} was equal to or more than the estimated value Q_u. Since the slab carried a part of the shear force, the shear force that was carried by stirrups was reduced. As a result, slab prevented stirrups fracturing.

5. Conclusions

Static loading test of the beams with nonstructural wall was carried out. The findings of this study were as follows:

(1) The beam with non-structural wall having structural gaps had the possibility of shear failure occurred, even though the beam had more than 1.1 of shear margin.
(2) By increasing the stirrups of beam end, the shear failure could be prevented.
(3) Existing of the slab prevented the expansion of the shear cracks, and could prevent to fail in shear manner.
(4) Although the evaluation method of stiffness need to be improved, the evaluation formula of strength were applicable by ignoring the walls. Cracking strength and flexural yielding strength could be evaluated in the historical formula by ignoring the wall.
(5) The shear force was separated into the components carried by beam and slab, and the shear force carried by the beam could be evaluated.

6. Acknowledgements

The part of this research has been supported by Scientific Research Grant Program under Grant-in-aid No. 25420572 in 2013-2016 and The Subsidies for the project of servicing the Architectural Standard from the MLIT, No. S6 in 2014. The authors would like to thank professors, the technical staff (Mr. Hatanaka), co-workers (Mr. Sauod and Ms. Tani), and students of RC Lab.

7. References

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