EXPERIMENTAL RERULTS AND VERIFICATION

Experimental Results

Behavior of test specimens

1. Specimen A1

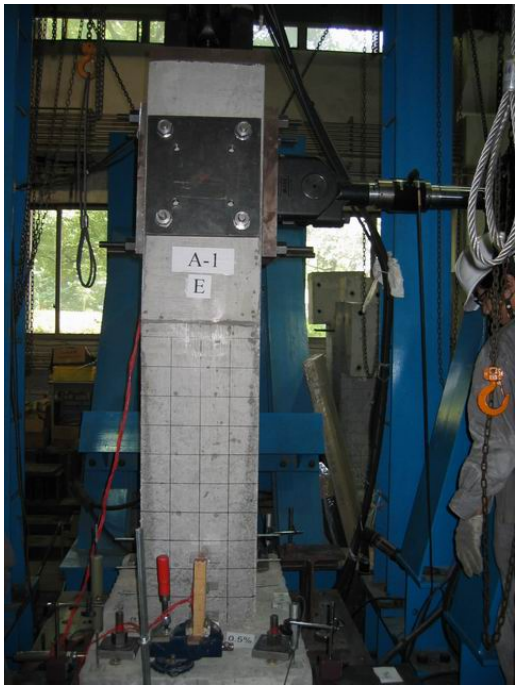


Figure 32 Specimen A1 test setup

Fig. 32 shows the test setup of the specimen A1. Specimen A1was subjected to an axial force of 384 kN where the axial force index was 0.074 $f_c^{'} A_g$. The cyclic displacement loading was applied in the west (W) and east (E) direction alternately. The displacement loading history started from drift ratio at 0.05% until failure at 6.5% as shown in Fig. 33.

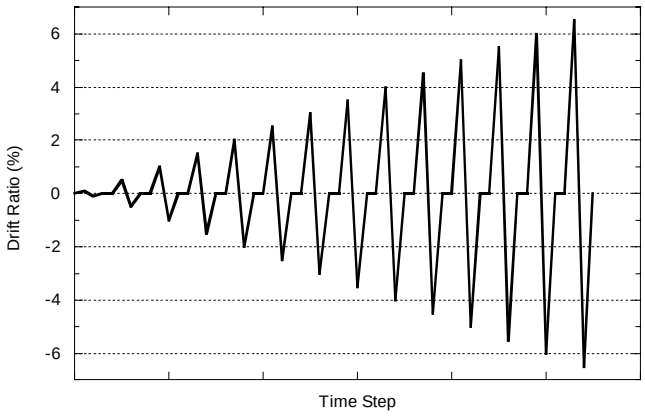


Figure 33 Displacement loading histories for specimens A1, A2, B1 and B2

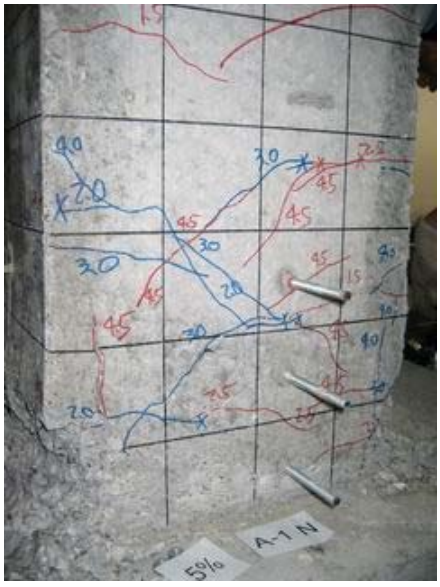
After flexural cracks appeared, vertical reinforcement strain measured was yielded at 0.76% drift ratio reached while the average measured R was 124.49 kN and Δ_Y was 11.75 mm. The hysterics under the displacement loading reached at its average maximum strength of 151.76 kN. When the drift ratio was 3%, the cover concrete surface started to spall off on the compression side. Then the cover concrete lump at the bottom spalled off increasing rate at 4.5 % drift ratio. When the drift ratio was 5.5 % at east side all vertical bars buckled and tie bars exposed outward completely. Then all vertical bars buckled followed by tie bars exposed completely at W side when drift ratio was 6 %. Finally, when the specimen was pushed of 6.5 % drift ratio, the core concrete was crushed and ten vertical bars totally were buckled. The severely damaged zone was 30 cm from the base.

a.) Perpendicular side with lateral force

b.) Parallel side with lateral force

Figure 34 Specimen A1 at 3.5 % drift ratio

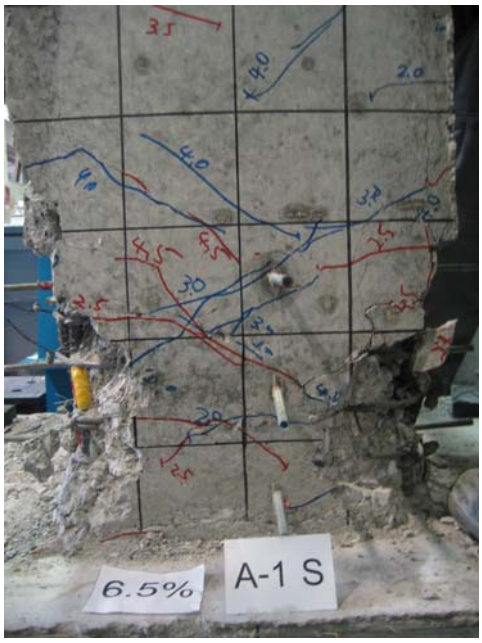
a.) Perpendicular side with lateral force



b.) Parallel side with lateral force

Figure 35 Specimen A1 at 5 % drift ratio

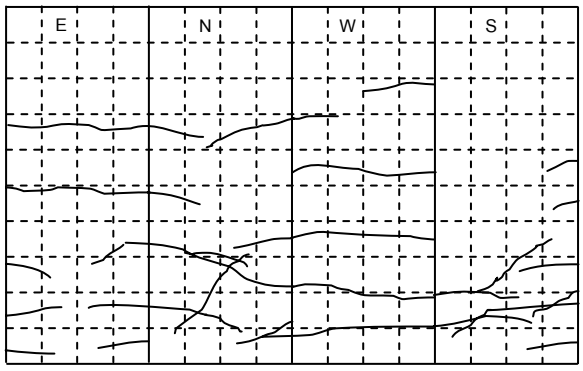
a.) Perpendicular side with lateral force



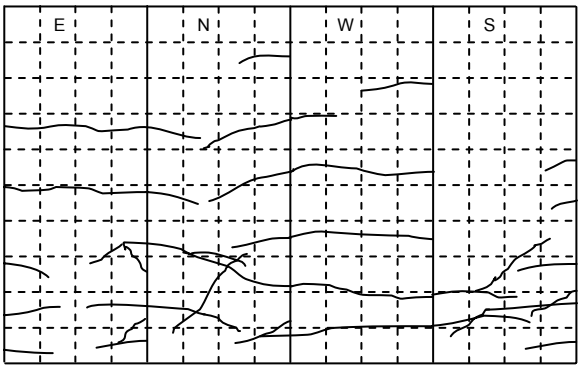
b.) Parallel side with lateral force

Figure 36 Specimen A1 at the end of test (drift ratio = 6.5 %)

Fig. 34 through Fig. 36 show the development during of the test and Fig. 37 shows the sketch of the progress of failure in the specimen A1.

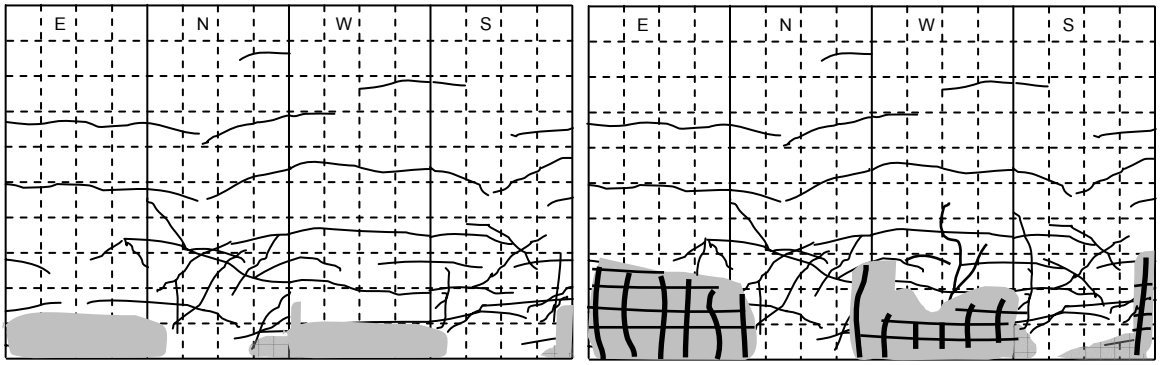


(a) Drift ratio at 3%



(b) Drift ratio at 4%

Figure 37 Progress of failure of specimen A1



(c) Drift ratio at 5% (d) Drift ratio at 6%

Figure 37 (Continued)

Measured strain in vertical reinforcement (E) and confinement (TE and TN) are shown in Fig. 39. After spalling of cover concrete, yielding of the tie rebar at the east side and west side was reached. The strain measured of tie rebar at N side (TN) and E side (TE) yielded at 3 % and 5% drift ratio respectively.

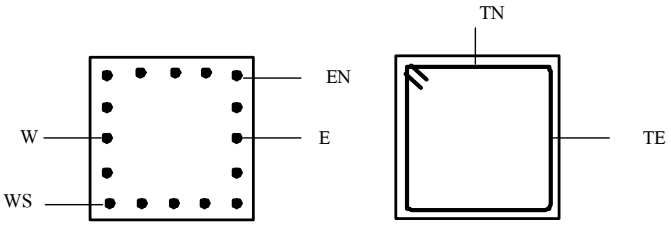


Figure 38 Attached strain gages of axial reinforcements and confinement steels of specimen A1

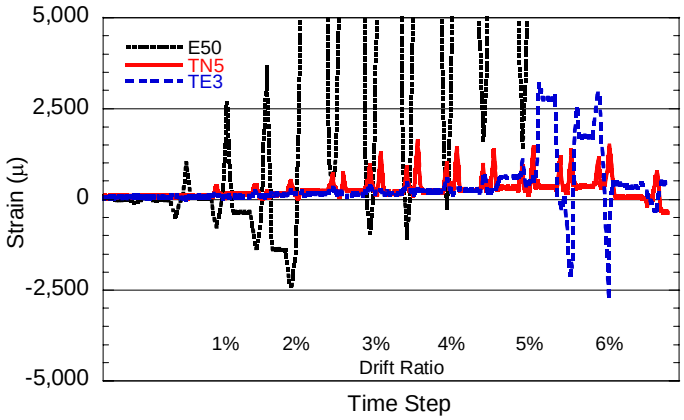


Figure 39 Measured strain of specimen A1

Fig. 40 presents the measured lateral force and lateral displacement hysteresis for specimen A1.

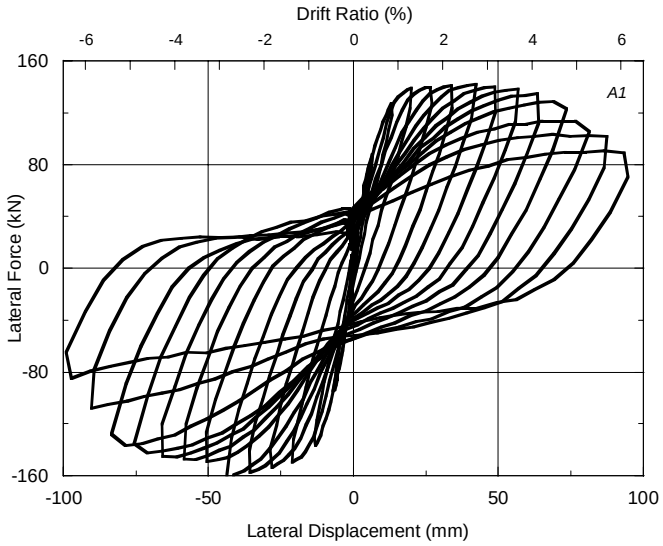


Figure 40 Lateral forces vs. lateral displacement hysteresis of specimen A1

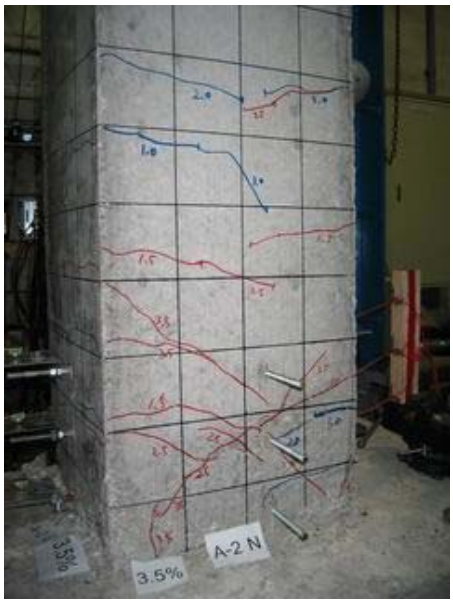
2. Specimen A2

Figure 41 Specimen A2 test setup

Fig. 47 shows the test setup of the specimen A2. Specimen A-2 was subjected to eccentric load by axial force and cyclic displacement loading. This eccentricity (e) equals 60 mm in north (N) side measured from the centre of the column to the point which applied axial load. The cyclic load was applied in perpendicular direction to the eccentricity. The applied axial force was 384 kN where the axial force index was $0.074 f_c^{'} A_g$. The cyclic displacement loading was applied in the west (W) and east (E) direction alternately and perpendicular direction to the eccentricity. Similar to specimen A1, the displacement loading history started from drift ratio at 0.05% until failure at 6.5% as shown in Fig. 33.

After flexural cracks appeared, vertical bar strain measured was yielded at 0.79% drift ratio reached while the average measured R was 121.13 kN and Δ_y was 12.19 mm. The hysterics under the displacement loading reached at its average maximum strength of 141.11 kN. When the drift ratio was 3%, the cover concrete surface started to spall off on the compression side. Then the cover concrete lump at the bottom spalled off increasing rate at 4.5 % drift ratio. When the drift ratio was 5.5 % at E side all vertical bars buckled and tie bars exposed outward completely. Then all vertical bars buckled followed by tie bars exposed completely at W side when drift ratio was 6 %. Finally, when the specimen was pushed of 6.5 % drift ratio, the core concrete was crushed and ten vertical bars totally were buckled. The severely damaged zone was 31cm from the base.

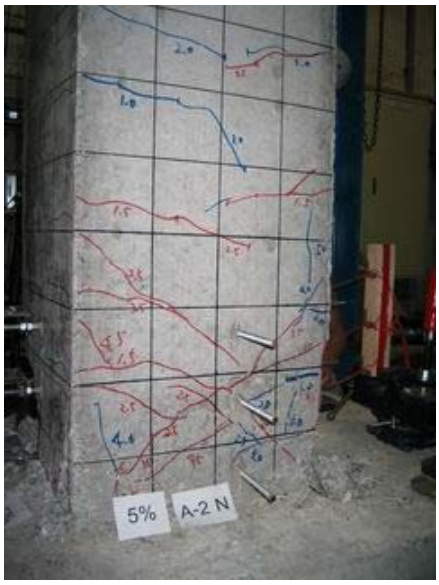
a.) Perpendicular side with lateral force



b.) Parallel side with lateral force

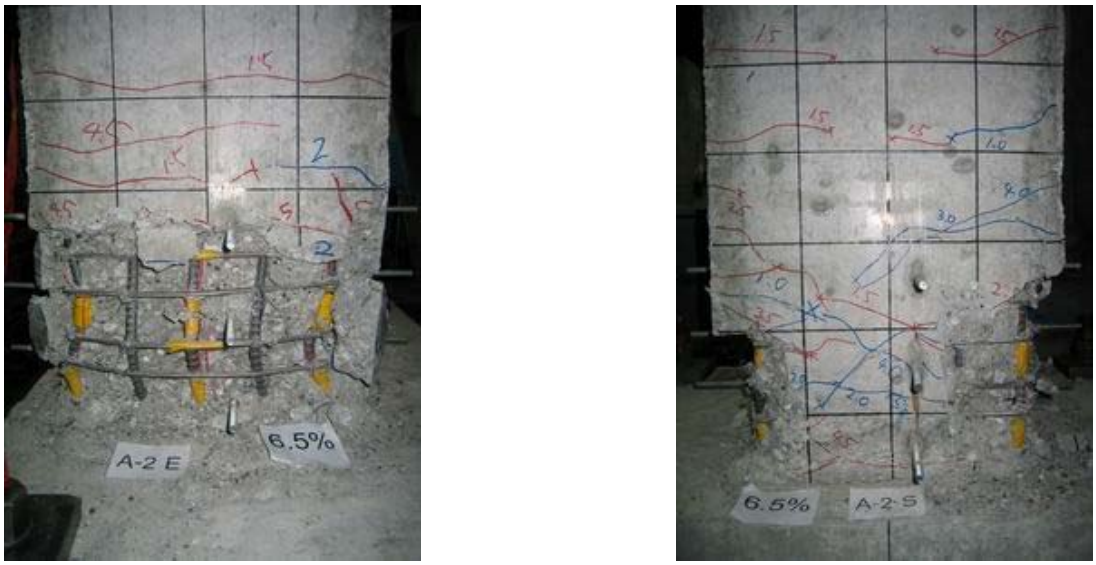
Figure 42 Specimen A2 at 3.5 % drift ratio

a.) Perpendicular Side with lateral force



b.) Parallel side with lateral force

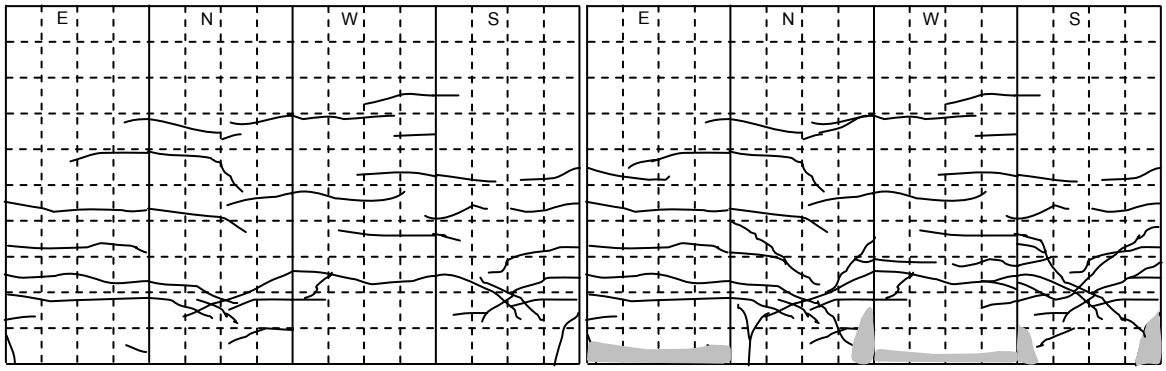
Figure 43 Specimen A2 at 5 % drift ratio



a.) Perpendicular side with lateral force b.) Parallel side with lateral force

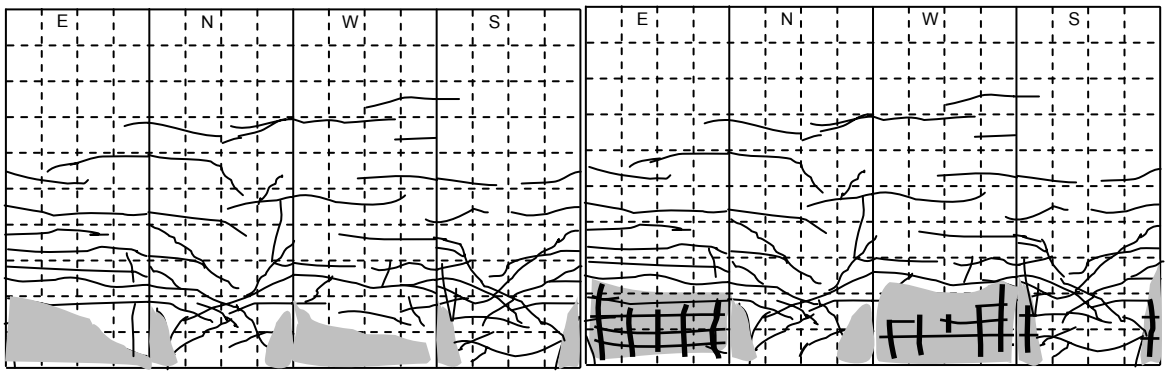
Figure 44 Specimen A2 at the end of test (drift ratio = 6.5 %)

Fig. 48 through Fig. 50 show the development during of the test and Fig. 51 shows the sketch of the progress of failure in the specimen A2.



(a) Drift ratio at 3% (b) Drift ratio at 4%

Figure 45 Progress of failure of specimen A2



(c) Drift ratio at 5% (d) Drift ratio at 6%

Figure 45 (Continued)

Measured strain in vertical reinforcement (E) and confinement (TE and TN) are shown in Fig. 47. After spalling of cover concrete, yielding of the tie rebar at the east side and west side was reached. The strain measured of tie rebar at N side (TN) and E side (TE) yielded at 4.5 % and 5.5 % drift ratio respectively.

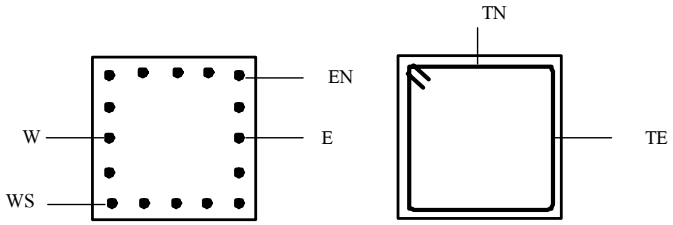


Figure 46 Attached strain gages of axial bars and confinement steel of specimen A2

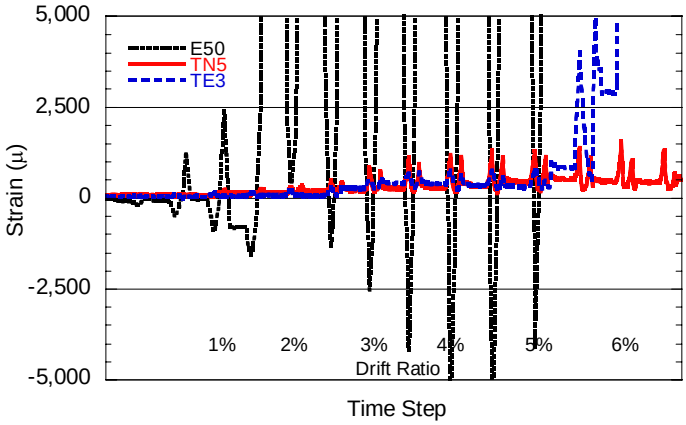


Figure 47 Measured strain of specimen A2

The lateral force and lateral displacement hysteresis for specimen A2 is shown in Fig. 48.

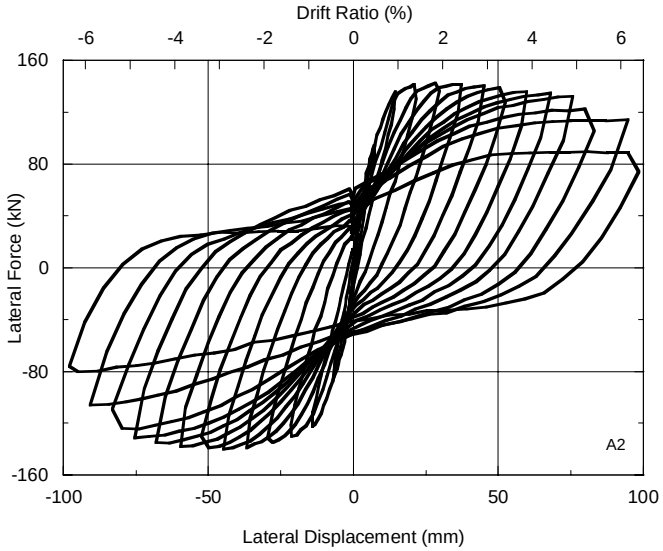


Figure 48 Lateral force vs. lateral displacement hytereses of specimen A2

3. Specimen B1

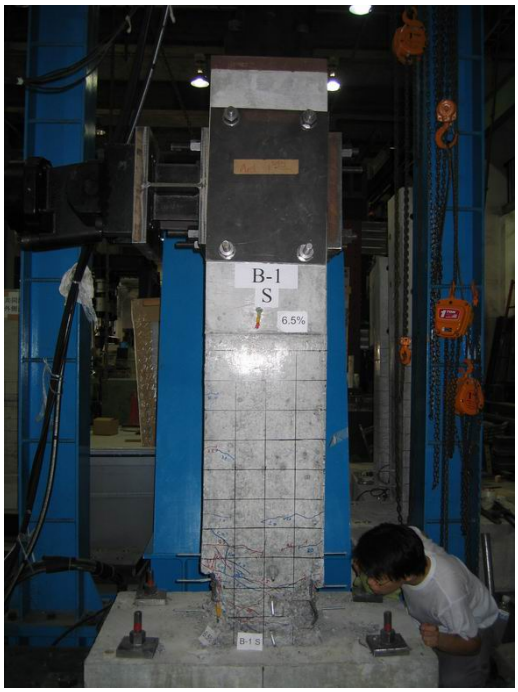


Figure 49 Specimen B1 test setup at failure

Specimen B-1was subjected to an axial force of 384 kN where the axial force index was $0.081 f_c' A_g$. The cyclic displacement loading was applied in the west (W) and east (E) direction alternately. Similar to specimen A1, the displacement loading history started from drift ratio at 0.05% until failure at 6.5% as shown in Fig. 33.

After flexural cracks appeared, vertical bar strain measured was yielded at 0.67% drift ratio reached while the average measured R was 121.17 kN and Δ_y was 10.40 mm. The hysterics under the displacement loading reached at its average maximum strength of 154.1 kN. When the drift ratio was 3.5%, the cover concrete surface started to spall off on the compression side. Then the cover concrete lump at the bottom spalled off increasing rate at 4 % drift ratio. When the drift ratio was 4.5 %, the cover concrete started to spall off and vertical bars at E/W corner buckled and exposed. When the drift ratio was 5.5 % vertical bars at all corners buckled and tie bars exposed outward. Then all vertical bars buckled followed by tie bars exposed completely at W side and E side when drift ratio was 6 %. Finally, when the specimen was pushed of drift ratio = 6.5 %, the core concrete was crushed and ten vertical bars were buckled and also two vertical bars were fractured. The severely damaged zone was 26 cm from the base.

a.) Perpendicular side with lateral force

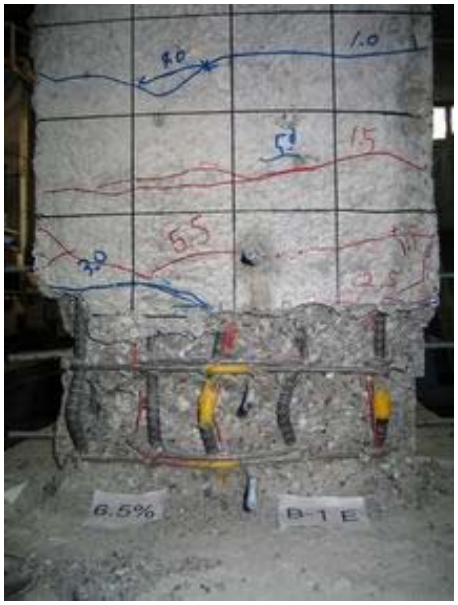
b.) Parallel side with lateral force

Figure 50 Specimen B1 at 3.5 % drift ratio

a.) Perpendicular side with lateral force

b.) Parallel side with lateral force

Figure 51 Specimen B1 at 5 % drift ratio

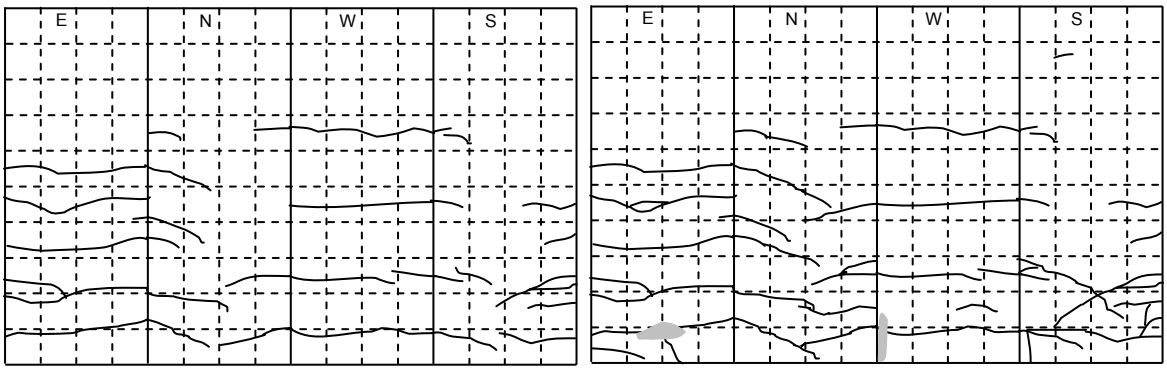


a.) Perpendicular side with lateral force

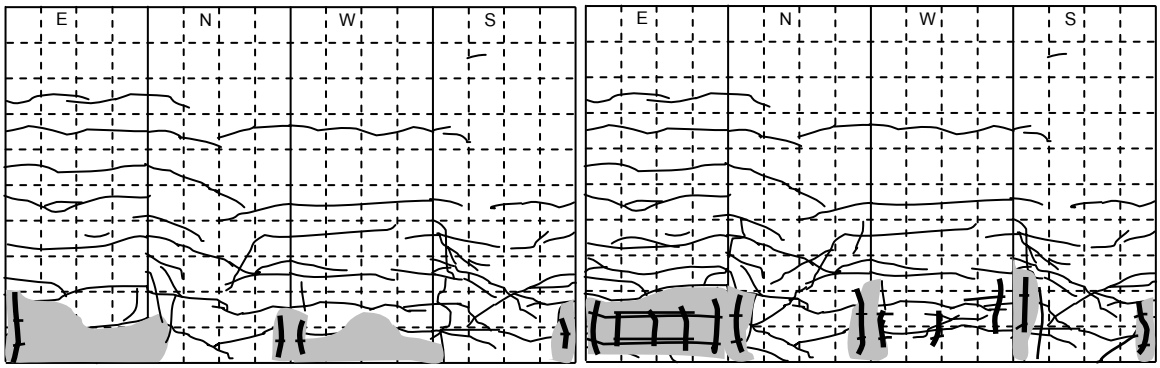
b.) Parallel side with lateral force

Figure 52 Specimen B1 at the end of test (drift ratio = 6.5 %)

Fig. 50 through Fig. 52 show the development during of the test and Fig. 53 shows the sketch of the progress of failure in the specimen B1. The lateral force and lateral displacement hysteresis for specimen B1 is shown in Fig.56.



a) Drift ratio at 3% d) Drift ratio at 4%



c) Drift ratio at 5% d) Drift ratio at 6%

Figure 53 Progress of failure of specimen B1

Measured strain in vertical reinforcement (E) and confinement (TE and TN) are shown in Fig. 55. After spalling of cover concrete, yielding of the tie rebar at the east side and west side was reached. The strain measured of outer ring of tie rebar at N side (TN) and E side (TE) yielded at 5 % and 1 % drift ratio respectively while inner ring of tie rebar at N side yielded at 5.5 % drift ratio.

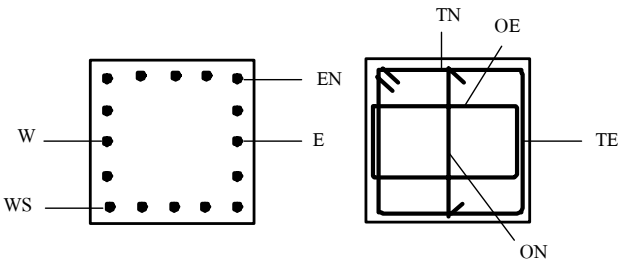
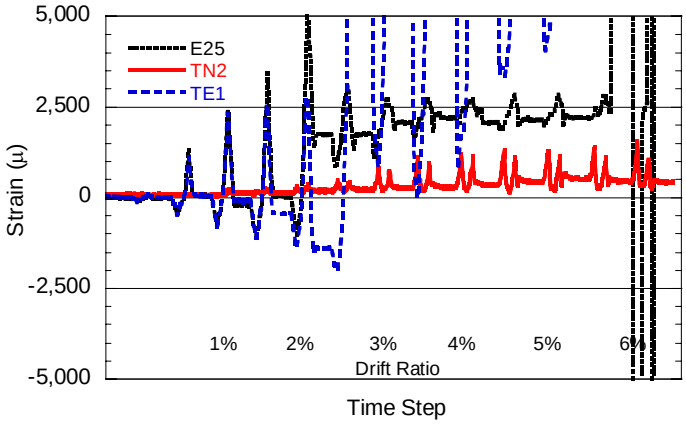
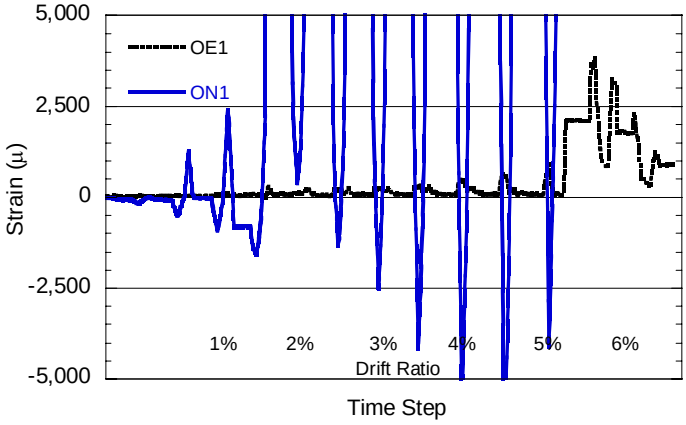


Figure 54 Attached strain gages of axial bars and confinement steel of specimen B1



a) Vertical reinforcement and out ring of confinement steel



b) Cross tie and inner confinement steel

Figure 55 Measured strain of specimen B1

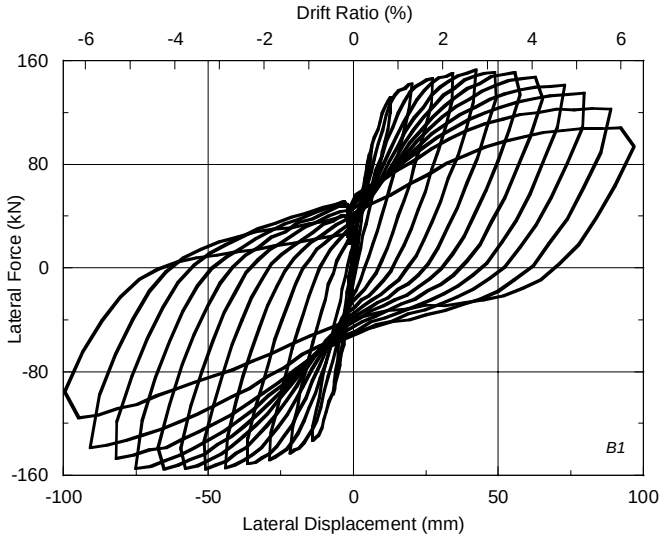


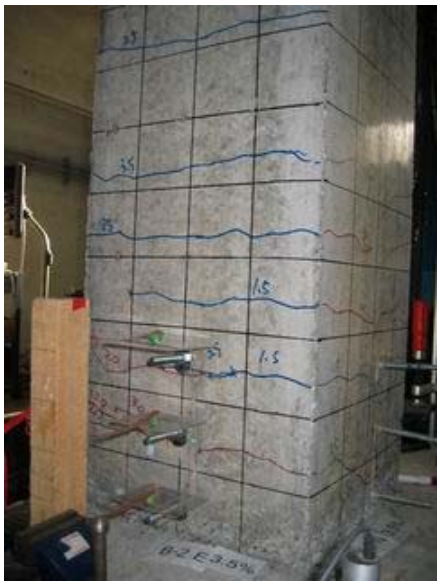
Figure 56 Lateral force vs. lateral displacement hytereses of specimen B1

4. Specimen B2

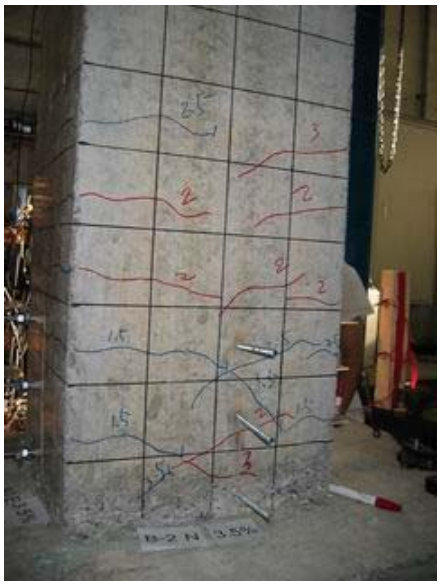
Specimen B-2 was subjected to eccentric load by axial force in eccentric loading and cyclic displacement loading. This eccentricity (e) equals 60 mm ($0.15D$) in north (N) side measured from the centre of the column to the point which axial applied load. The cyclic load was applied in perpendicular direction to the eccentricity. The applied axial force was 384 kN where the axial force index was $0.081 f_c^{'} A_g$. The cyclic displacement loading was applied in the west (W) and east (E) direction alternately and perpendicular direction to the eccentricity. Similar to specimen A1, the displacement loading history started from drift ratio at 0.05% until failure at 6.5% as shown in Fig. 33.

After flexural cracks appeared, vertical bar strain measured was yielded at 0.69 % drift ratio reached while the average measured P_H was 113.1 kN and Δ_Y was 10.66 mm. The hysterics under the displacement loading reached at its average maximum strength of 141.23 kN. When the drift ratio was 4%, the cover concrete surface started to spall off on the compression side. Then the cover concrete lump at the bottom spalled off increasing rate at 4.5 % drift ratio.
When the drift ratio was 5 % vertical bars at all corners buckled and tie bars exposed outward. When the drift ratio was 5.5 % at W side, all vertical bars buckled and ties bar exposed outward. Then all vertical bars buckled followed tie bars exposed completely at east side when drift ratio

was 6 %. Finally, when the specimen was pushed of drift ratio = 6.5 %, the core concrete was crushed and twelve vertical bars were buckled. The severely damaged zone was 28 cm from the base.



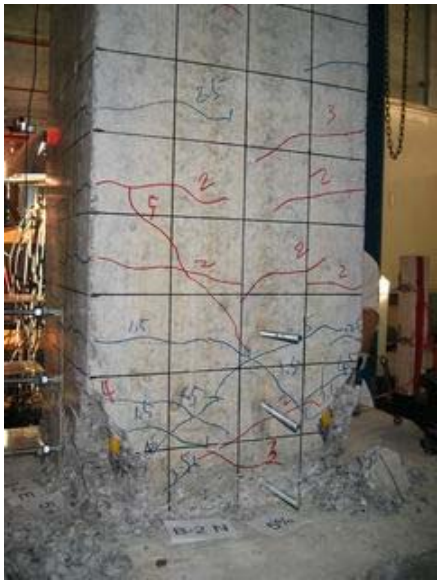
a.) Perpendicular side with lateral force



b.) Parallel side with lateral force

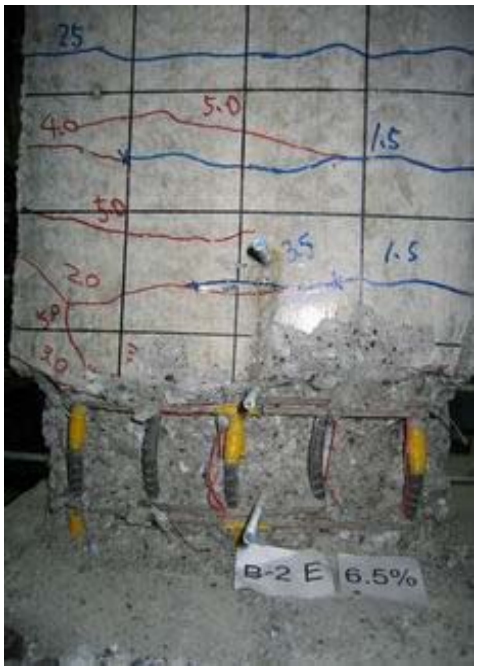
Figure 57 Specimen B2 at 3.5 % drift ratio

a.) Perpendicular side with lateral force



b.) Parallel side with lateral force

Figure 58 Specimen B2 at 5 % drift ratio



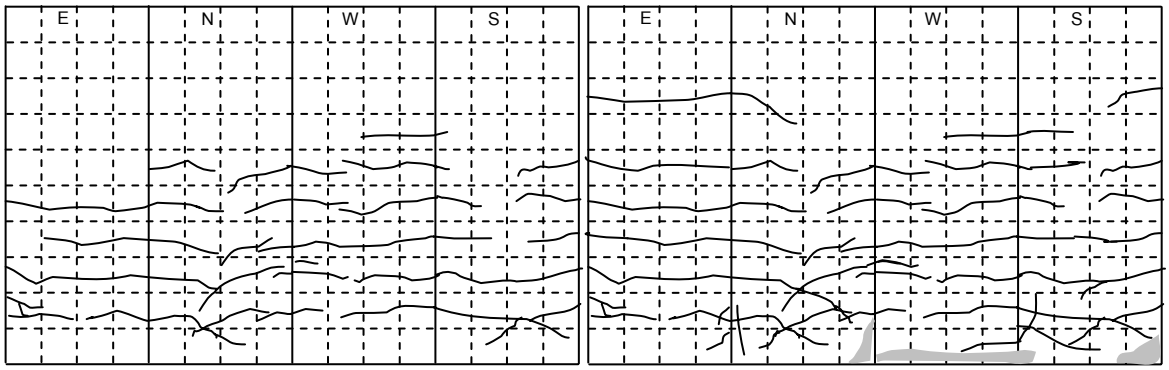
a.) Perpendicular side with lateral force

b.) Parallel side with lateral force

Figure 59 Specimen B2 at the end of test (drift ratio = 6.5 %)

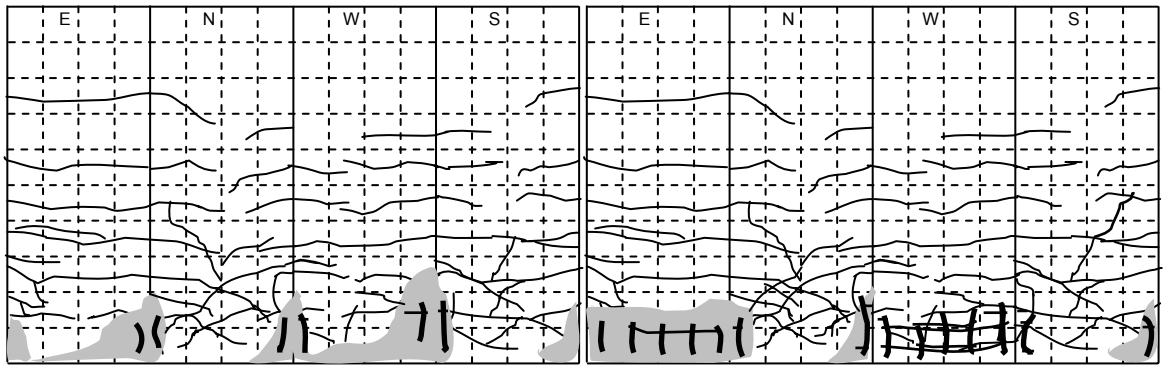
Fig. 57 through Fig. 59 show the development during of the test and Fig. 61 shows the sketch of the progress of failure in the specimen B1. Fig. 60 shows the test setup of the specimen B2 at the end of test.

Figure 60 Specimen B2 test setup at the end of test



(a) Drift ratio at 3% (b) Drift ratio at 4%

Figure 61 Progress of failure of specimen B2



(c) Drift ratio at 5% (d) Drift ratio at 6%

Figure 61 (Continued)

Measured strain in vertical reinforcement (E) and confinement (TE and TN) are shown in Fig. 63. After spalling of cover concrete, yielding of the tie rebar at the east side and west side was reached. The strain measured of outer ring of tie rebar at N side (TN) and E side (TE) yielded at 3.5 % and 5.5 % drift ratio respectively while inner ring of tie rebar at N side yielded at 4 % drift ratio.

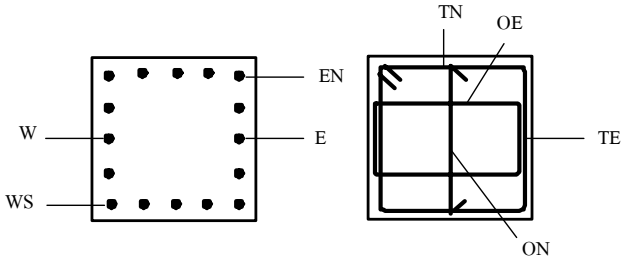
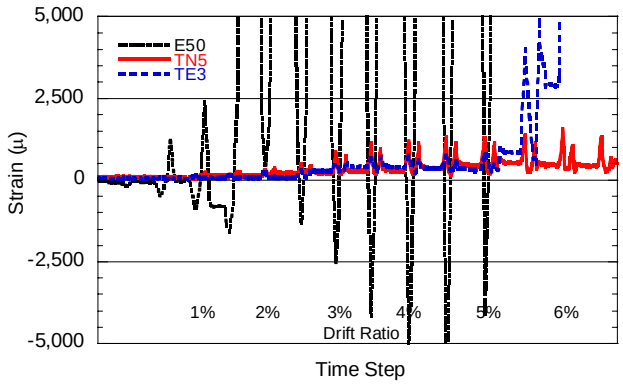
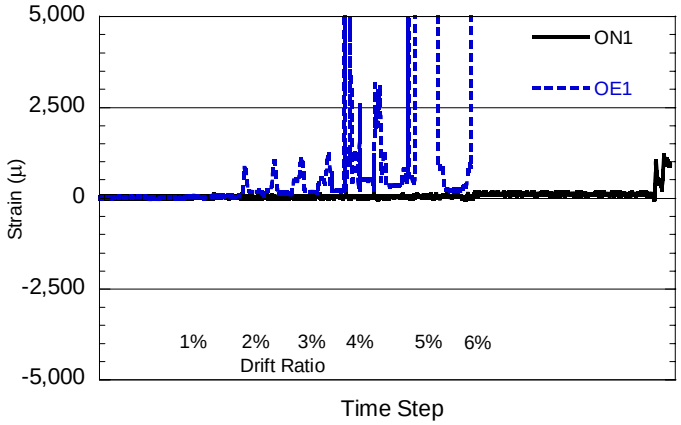


Figure 62 Attached strain gages of axial bars and ties bars of specimen B2



a) Vertical reinforcement and out ring of confinement steel

Figure 63 Measured strain of specimen B2



b) Cross tie and inner confinement steel

Figure 63 (Continued)

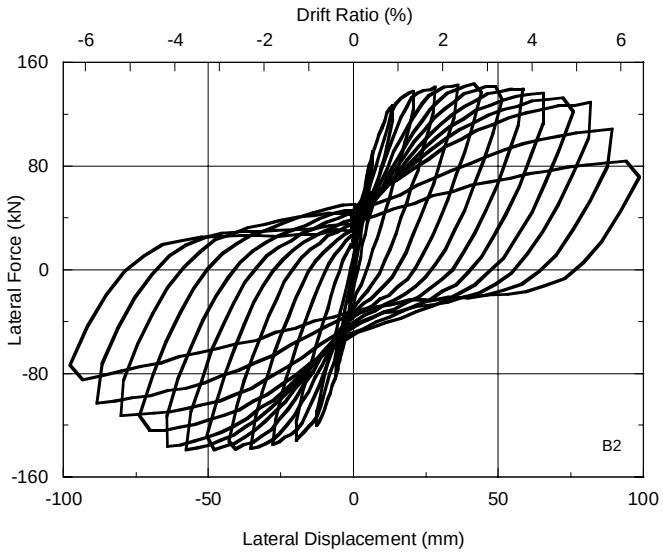


Figure 64 Lateral force vs. lateral displacement hytereses of specimen B2

5. Specimen C-1

Figure 65 Specimen C1 test setup

Specimen C-1was subjected to an axial force of 384 kN where the axial force index was $0.074 f_c^{'} A_g$. Fig. 65 shows the test setup of the specimen C1. The cyclic displacement loading was applied in the west (W) and east (E) direction alternately. The displacement loading history started from drift ratio at 0.05% until failure at 5% as shown in Fig. 66.

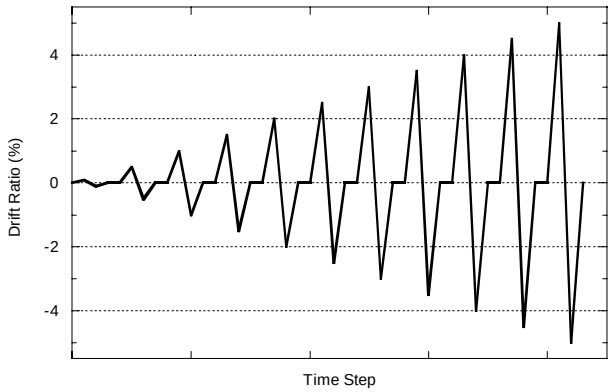


Figure 66 Displacement loading histories for specimens C1

After flexural cracks appeared, vertical bar strain measured was yielded at 0.76% drift ratio reached while the average measured *R* was 132.41 kN and Δ_Y was 13.51 mm. The hysterics under the displacement loading reached at its average maximum strength of 144.52 kN. When the drift ratio was 3%, the cover concrete surface started to spall off on the compression side. Prior to 4 % drift ratio the cover concrete plate spalled off and vertical bars and ties bar exposed completely at E side followed. When the drift ratio was 4.5 % the vertical bars at all corners buckled and ties bar exposed outward. Then all vertical bars totally buckled followed by tie bars at W side and E side when drift ratio was 5 %. Finally, brittle flexure-shear failure occurred. The severely damaged zone was 43 cm from the base.

a.) Perpendicular Side with Lateral Force

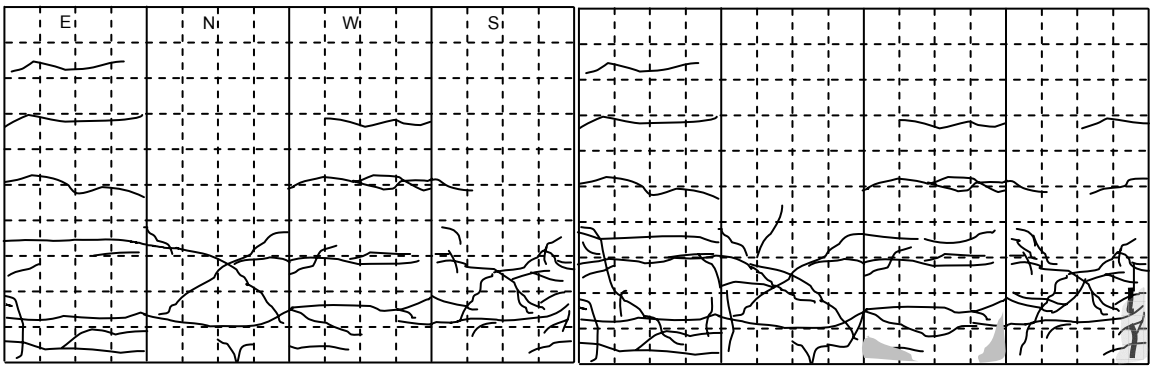
b.) Parallel side with Lateral Force

Figure 73 Specimen C1 at 3.5 % drift ratio

a.) Perpendicular Side with Lateral Force b.) Parallel side with Lateral Force

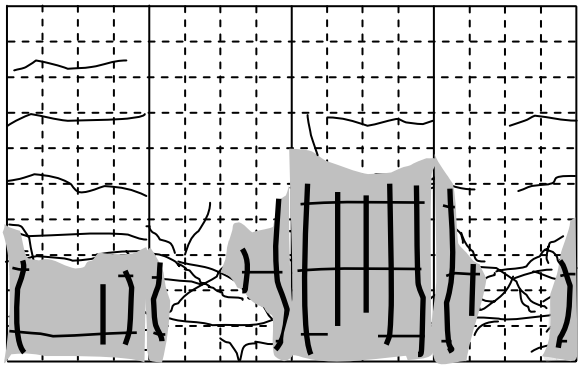
Figure 68 Specimen C1 at the end of test (drift ratio = 5 %)

Fig.73 and Fig. 74 show the development during of the test and Fig. 75 shows the sketch of the progress of failure in the specimen C1.



(a) Drift ratio at 3% (b) Drift ratio at 4%

Figure 69 Progress of failure of specimen C1



(c) Drift Ratio 5%

Figure 69 (Continued)

Measured strain in vertical reinforcement (E) and confinement (TE and TN) are shown in Fig. 71. After spalling of cover concrete, yielding of the tie rebar at the east side and west side was reached. The strain measured of tie rebar at N side (TN) and E side (TE) yielded at 3 % and 5% drift ratio respectively.

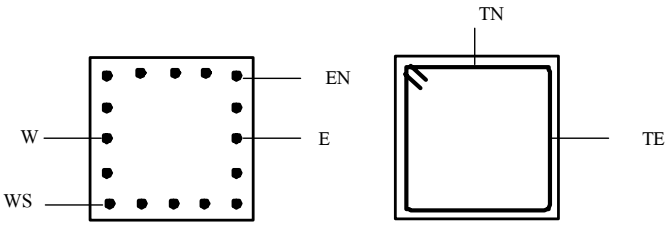


Figure 70 Attached strain gages of axial bars and confinement steel of specimen C1

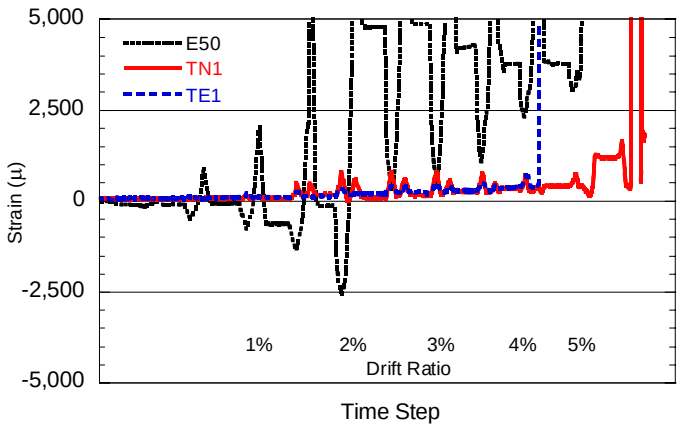


Figure 71 Measured strain of specimen C1

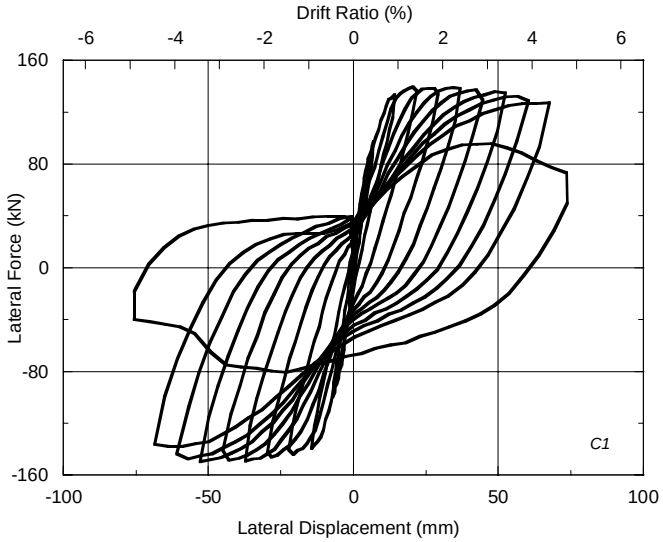


Figure 72 Lateral force vs. lateral displacement hytereses of specimen C1

6. Specimen D-1

Specimen D-1was subjected to an axial force of 384 kN where the axial force index was $0.081 f_c^{'} A_g$. The cyclic displacement loading was applied in the west (W) and east (E) direction alternately. The displacement loading history started from drift ratio at 0.05% until failure at 5.5% as shown in Fig. 74.

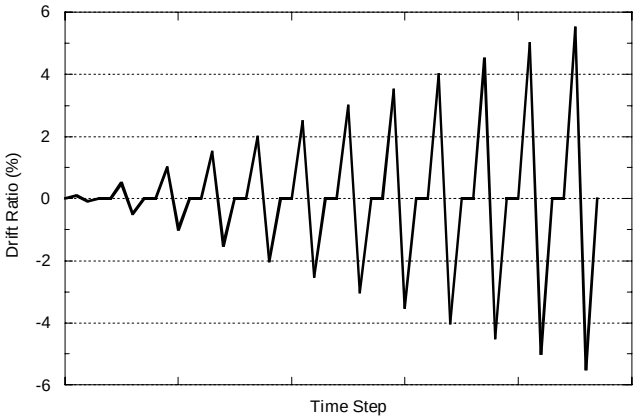
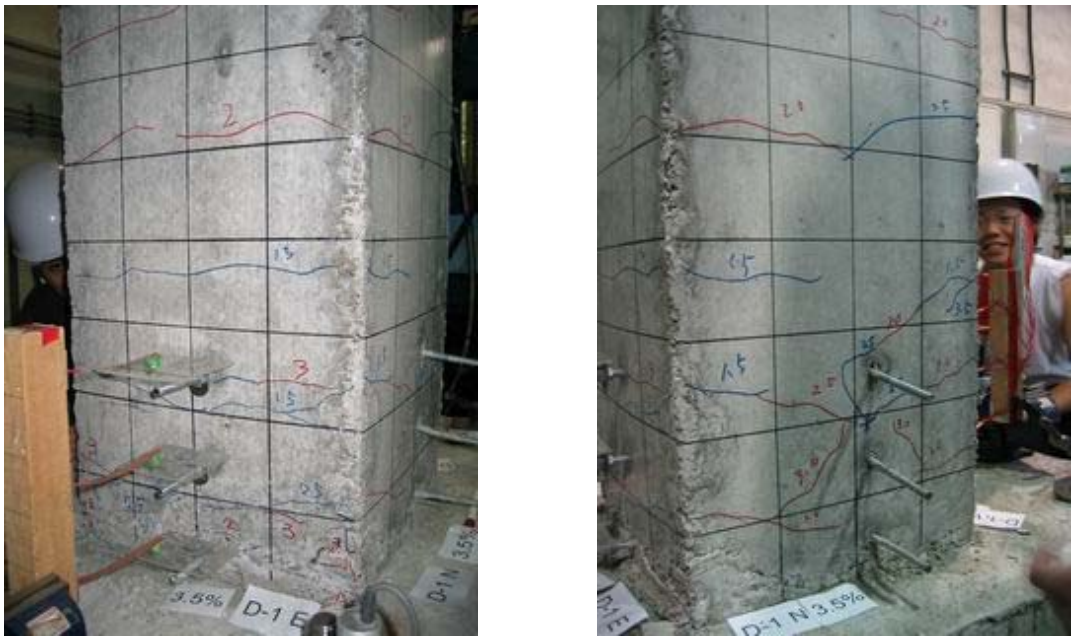


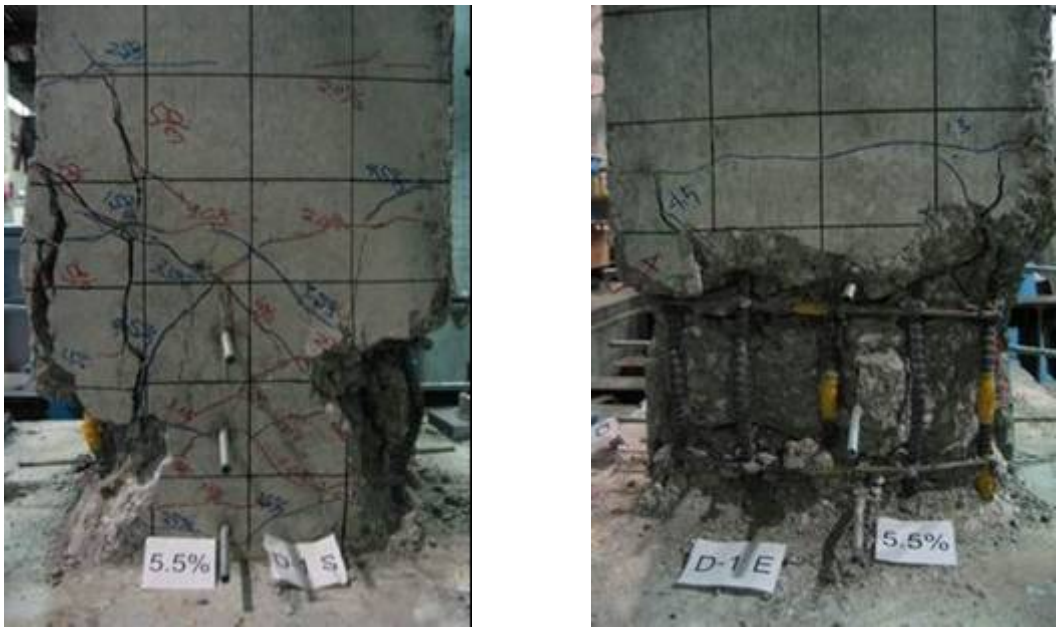
Figure 73 Displacement loading histories for specimens D1

After flexural cracks appeared, vertical bar strain measured was yielded at 0.71% drift ratio reached while the average measured P_H was 126.95 kN and Δ_Y was 11.04 mm. The hysterics under the displacement loading reached at its average maximum strength of 126.95 kN. When the drift ratio was 3% the cover concrete surface started to spall off on the compression side. Then the cover concrete lump at the bottom spalled off increasing rate at 3.5 % drift ratio. When the drift ratio was 4 % the vertical bars at the corners buckled and tie bars exposed outward. Then all vertical bars buckled and ties bar exposed completely at E side when drift ratio was 4.5 %. Then all vertical bars buckled and ties bar exposed completely at W side followed with significant stiffness degradation when drift ratio was 5 %. Finally, when the specimen was pushed of 5.5 % drift ratio, the core concrete was crushed and twelve vertical bars were buckled. The severely damaged zone was 35 cm from the base. The strain measured of tie bars at N side and E side yielded at 2 % and 5 % drift ratio respectively.



a.) Perpendicular side with lateral force b.) Parallel side with lateral force

Figure 74 Specimen D1 at 3.5 % drift ratio



a.) Perpendicular side with lateral force b.) Parallel side with lateral force

Figure 75 Specimen D1 at the end of Test (drift ratio = 5.5 %)

Fig. 73 and Fig. 75 show the development during of the test and Fig. 77 shows the sketch of the progress of failure in the specimen D1. Fig. 76 shows the test setup of the specimen D1 at the end of test.

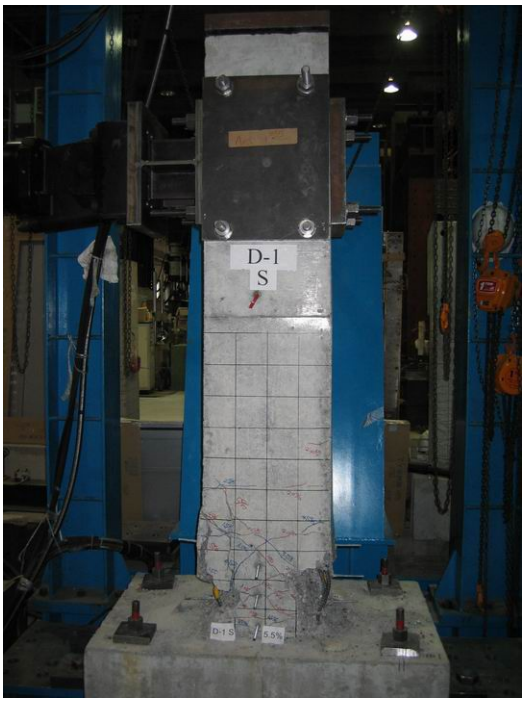
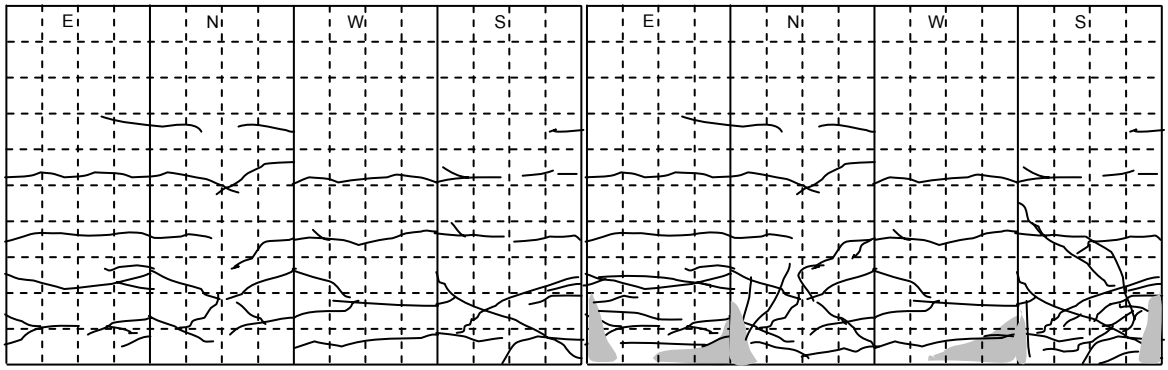
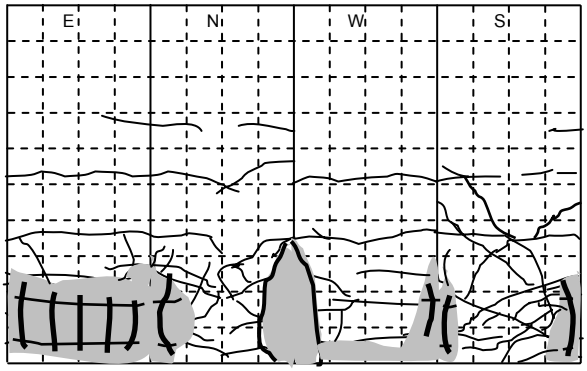


Figure 76 Specimen D1 test setup at the end of test



(a) Drift ratio at 3% (b) Drift ratio at 4%

Figure 77 Progress of failure of specimen D1



(c) Drift ratio 5%

Figure 77 (Continued)

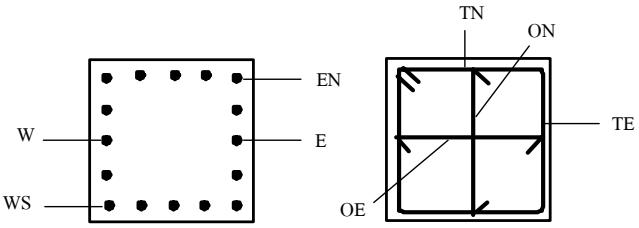


Figure 78 Attached strain gages of axial bars and confinement steel D1

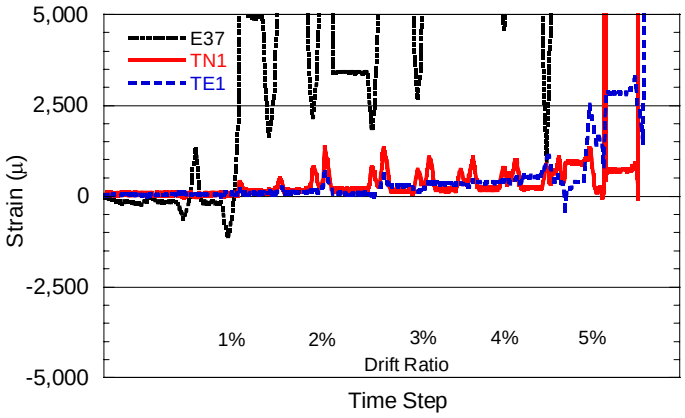


Figure 79 Measured strain of specimen D1

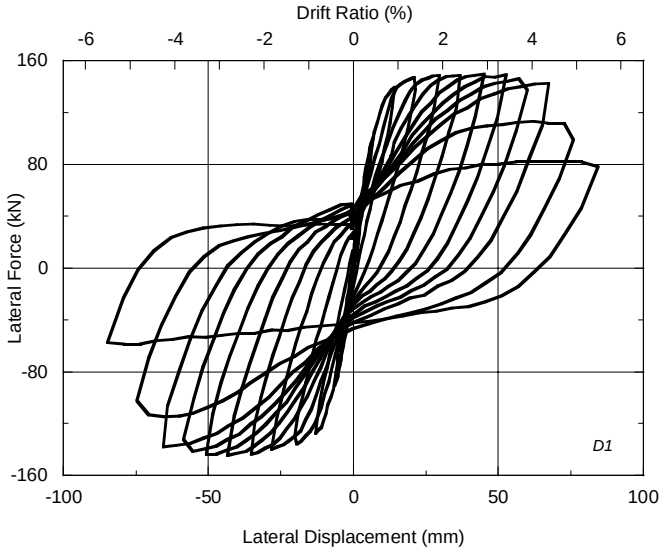


Figure 80 Lateral force vs. lateral displacement hytereses of specimen D1

Ductility factor

At yield of vertical displacement, the lateral displacement was measure. In this research, the occurred failure and the maximum displacement, Δ_u was defined in two difference models.

The first Δ_{u1} shown in column 5 of Table 5 is defined as the displacement at the horizontal force deteriorated to 75% of maximum horizontal force, R_{max} on the descending branch base on Wehbe et al. (1999).

According to Hoshikuma et al. (1997), the second Δ_{u2} shown in column 6 of Table 5 is defined when the compressive stress in core concrete, f_c on the descending branch was beyond 50% of the core concrete peak stress (f'_{cc}), crushing of core concrete and bucking of longitudinal reinforcement occurred. The lateral strain in concrete core at failure is the axial strain times the Poisson ratio of 0.2. This is also the strain in the tie bars and the drift ratios can be recorded.

The ductility factor, μ is the ratio of maximum displacement and yielding displacement as Equation (39). Table 5 gives the experimental results and the ductility factor.

$$\mu = \frac{\Delta_{u2}}{\Delta_y} \tag{39}$$

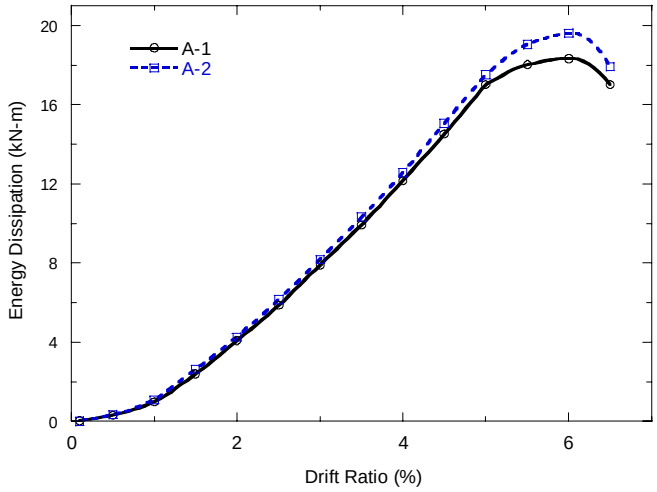
Energy Dissipation Capacity

The dissipation energy (ΔW_i) in one loop of hysteresis displacement is determined by integrating the area bounded by the hysteresis loop as indicated by Equation (40). The accumulated dissipation energy (ΔW) in the column specimens is determined by Equation (41).

$$\Delta W_i = \int_{-u_{\max}}^{u_{\max}} (F_l(u) - F_{ul}(u))du \tag{40}$$

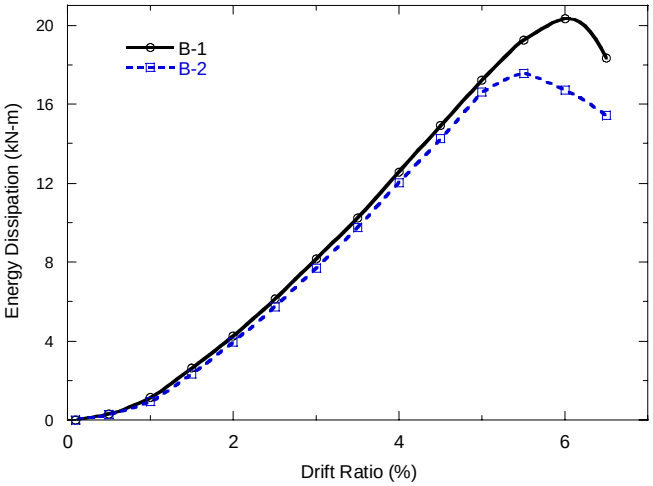
$$\Delta W = \sum_i \Delta W_i \tag{41}$$

where $F_l(u)$ and $F_{ul}(u)$ are the forces at displacement, u during loading and unloading process. Fig. 87 shows the dissipated energy vs. drift ratio of the test specimens.

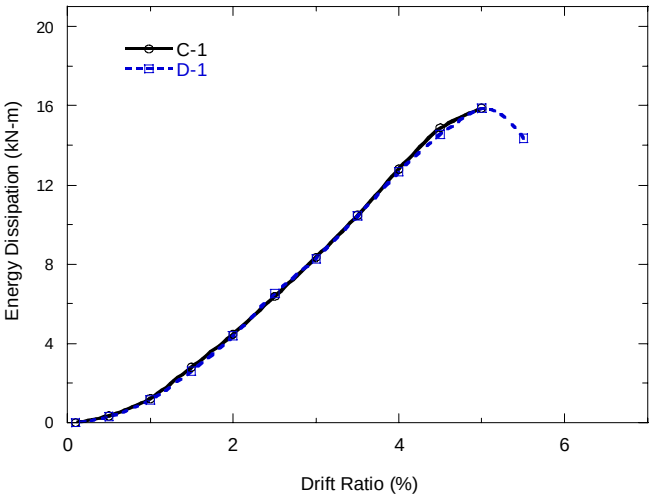


a) Specimen A1 and A2

Figure 81 Energy dissipation vs. lateral displacement of specimens



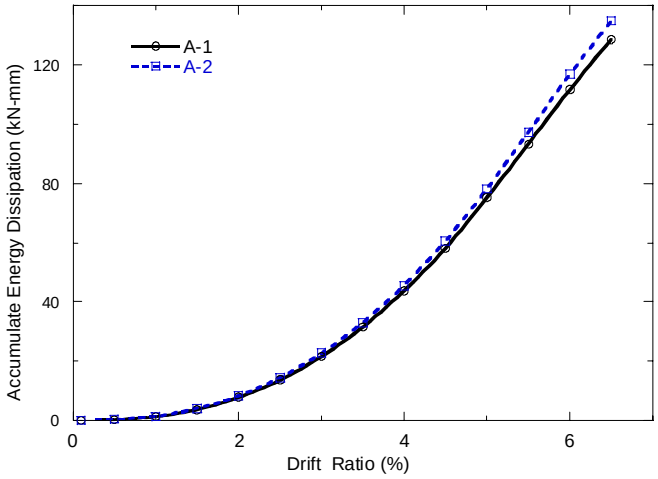
b) Specimen B1 and B2



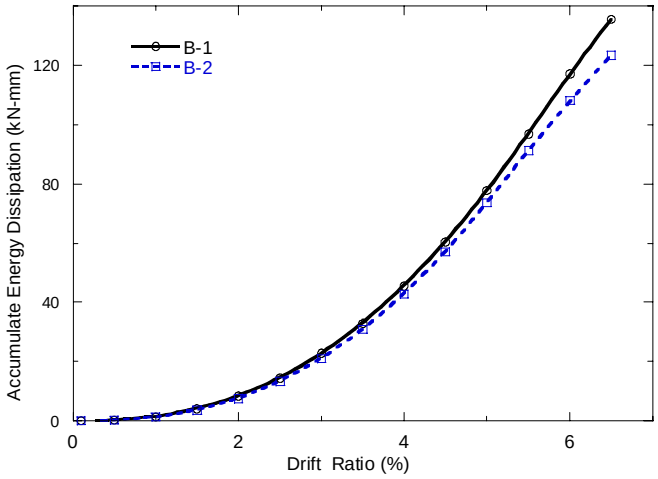
c) Specimen C1 and D1

Figure 81 (Continued)

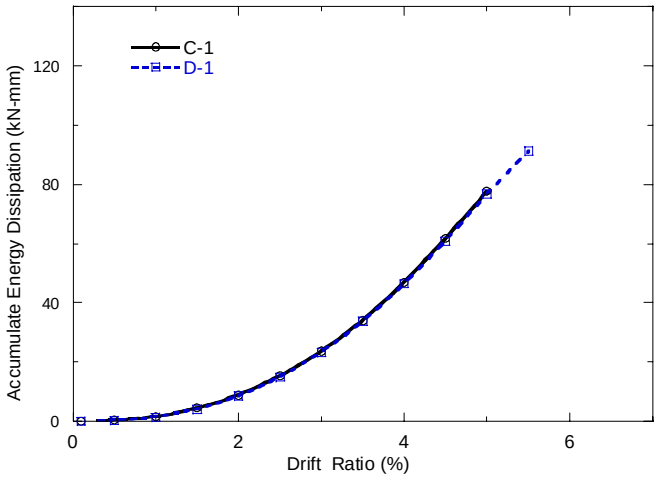
Fig. 82 shows the accumulate energy dissipation calculated by Equation (41).



a) Specimen A1 and A2



b) Specimen B1 and B2

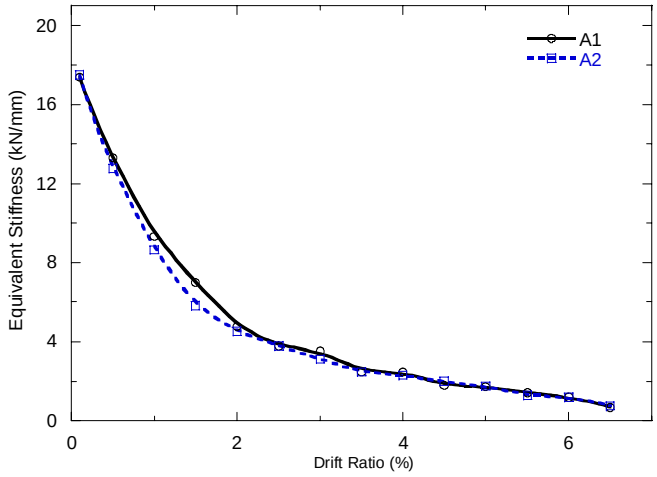


c) Specimen C1 and D1

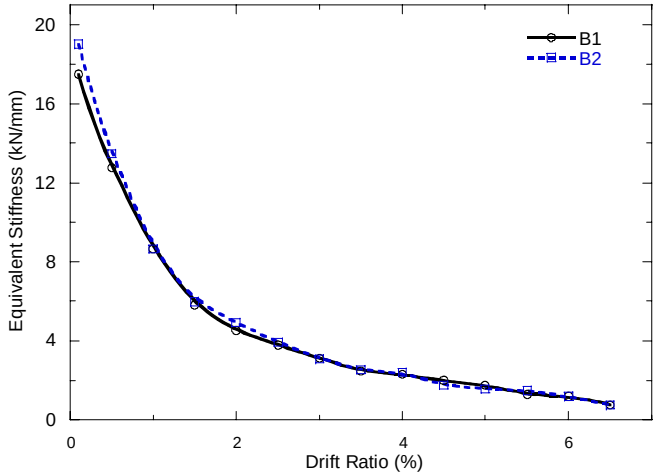
Figure 82 Accumulate energy dissipation vs. lateral displacement of test specimens

Equivalent Stiffness

The equivalent stiffness was determined by the ratio between the horizontal force and displacement range in each loading step. Fig. 89 shows the equivalent stiffness vs. drift ratio of the test specimens.

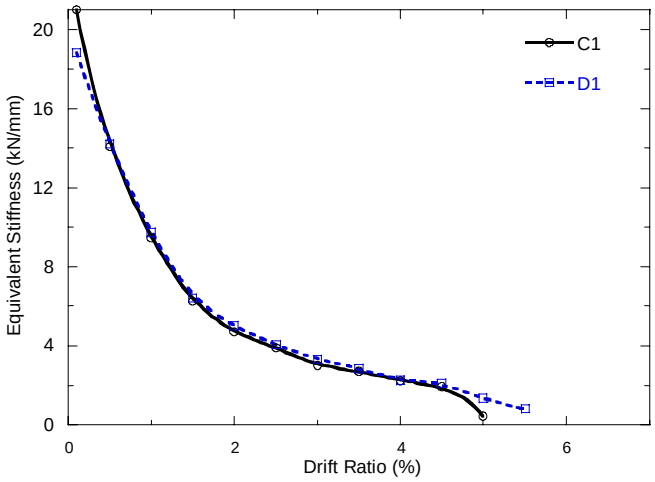


a) Specimen A1 and A2



b) Specimen B1 and B2

Figure 83 Equivalent stiffness vs. lateral displacement of test specimens



c) Specimen C1 and D1

Figure 83 (Continued) Equivalent stiffness vs. lateral displacement of test specimens

Summary of Experimental Results

A summary of the test results such as yielding load and displacement, maximum load, ultimate displacement and dissipated energy are presented in Table 5.

Table 5 **Test results**

Specimens	Yielding load, R_y (kN)			Yielding displacement, Δ_y (mm)			Maximum load, R_{max} (kN)			Δ_{u1} at 75% of R_{max} (mm)	Δ_{u2} at $f_c = f_{cc}/2$ (mm)	$\mu = \Delta_{u2}/\Delta_y$	Accumulate dissipated energy (kN-mm)	Failure mode
	+	-	Average	+	-	Average	+	-	Average					
A-1	126.9	122.1	124.5	13.0	10.5	11.7	142.0	161.5	151.8	85.1	70.2	6.0	128.6	Flexure
A-2	125.4	116.8	121.1	12.2	12.2	12.2	142.4	139.8	141.1	89.4	51.3	4.2	134.8	Flexure
B-1	119.4	123.0	121.2	10.0	10.8	10.4	152.9	155.4	154.1	92.5	79.5	7.6	135.5	Flexure
B-2	114.9	111.3	113.1	10.7	10.6	10.7	143.4	139.1	141.2	85.8	56.9	5.3	123.4	Flexure
C-1	130.5	134.3	132.4	14.6	12.4	13.5	139.4	149.7	144.5	70.0	46.5	3.4	77.6	Flexure-Shear
D-1	131.2	122.7	126.9	11.1	11.0	11.0	150.0	144.4	147.2	73.7	54.3	4.9	91.1	Flexure