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SEISMIC PROVING TEST OF CONCRETE CONTAINMENT VESSELS
PART 1: MODEL TESTS OF A CURVED SHEAR WALL FOR THE PCCV

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ABSTRACT

Since 1980 a series of seismic proving tests of nuclear power facilities has been carried out by the Nuclear Power Engineering Corporation (NUPEC), using the large-scale, high-performance shaking table at the Tadotsu Engineering Laboratory. The tests are sponsored by the Ministry of International Trade and Industry (MITI) of Japan.

As a part of this overall program, NUPEC is planning to conduct seismic proving tests for a PWR Prestressed Concrete Containment Vessel (PCCV), and a BWR Reinforced Concrete Containment Vessel (RCCV). The objectives of the tests are to prove the structural and functional integrity of a PCCV and an RCCV for the design earthquake S1 combined with the design pressure, and for the design earthquake S2 unpressurized. In addition, seismic margin tests of a PCCV and an RCCV will be conducted. The PCCV test model is now under construction and the vibration test will be conducted in 1997 at the Tadotsu Engineering Laboratory. The RCCV test model is now being designed and the vibration test will be conducted in 1998. The tests will be the first large-scale vibration test for each CCV with a liner to find their behavior during earthquakes including the interaction between the concrete portion and the liner system.

The concrete portion of the PCCV test model is a 1/10 scale representation of an actual PCCV in Japan. However, some modifications are needed such as a thick slab in lieu of the dome, and additional masses attached to this slab to maintain an vibrational characteristics equivalent to those of the PCCV. The steel liner plate is attached to the inner surface of the concrete wall using the same type of anchorage used in the actual PCCV. The scale used for the liner plate is 1/4 (1.6 mm thickness), which is different from the scale used for the concrete portion. Also, the scale of the wall thickness is 1/8 in order to accommodate the tendons, rebars and liner anchors.

The behavior of the liner of the test model could differ from that of the actual PCCV due to the unequal scaling. Therefore, auxiliary tests using curved PCCV wall specimen were conducted in order to confirm the adequacy of the PCCV test model. This paper mainly addresses the test results of the curved shear wall tests.

KEYWORDS

Seismic proving test, PCCV, Curved shear wall, Liner system, Horizontal loading.

PURPOSE OF THE TEST

The lower part of the PCCV is considered to be critical to withstand seismic loads. The purpose of this test was to determine the effect of the different scale factor of liner anchor and the curvature of the cylindrical portion of the concrete on the interaction behavior of the liner system (liner plate and anchors) and the concrete wall.

Due to constructability, the thickness of the liner plate had to be made to a scale of 1/4 whereas the concrete portion of the seismic proving test model was made to a scale of 1/10. The scale factor for the height of the web and the width of the flange of the liner anchor was fixed at 1/8 to avoid interference with the reinforcing bars in the concrete wall. Hence it is possible that the anchoring condition of the liner to the concrete in the seismic proving test model may not be an appropriate modeling of the actual structure.
When the cylindrical portion of the PCCV is subjected to a seismically induced in-plane shear force, tensile forces and shear forces are imposed on the anchors which secure the liner to the concrete wall when the behavior of the concrete is inelastic.
Fig. 1 shows a comparison of the PCCV wall shear test specimens used in this experiment with the actual PCCV structure and the seismic proving test model.

SPECIMENS

Table 1 is specifications of specimens used. Figure 2 gives a detailed description of each part of each system. Three alternative specimens were chosen with different combinations of scales.
The main parameters are scale of the concrete wall curvature and the scale of the liner system. M/QD (shear span ratio) of these specimens is 0.85 (nearly equal to the seismic proving test model).
Table 2 shows the test results of concrete and liner plate, and Table 3 shows the test results of the curved shear wall test specimens.

TEST METHOD

1. Method of applying force

Horizontal force was applied to the specimen with the base slab fixed to the test floor. Horizontal force was loaded by means of the loading slab.
Horizontal force was applied by pushing and pulling the loading slab with hydraulic jacks. The ratio of pushing force to whole force was 0.7. The center of the loading slab was aligned with the center of rigidity when the wall was elastic.
Prior to applying the horizontal load, prestressing forces (circumferential: 79.5 kgf/cm^2, vertical: 79.0 kgf/cm^2) equivalent to those of the actual structure were applied to the specimen vertically and horizontally. The force-application appartus is shown in Fig. 3. The applied forces of seismic loads S1 and S2 were applied two times each in positive and negative alternation. Next, after alternately applying positive and negative relative displacement of displacement angle R=1 x 10^{-3}, 2 x 10^{-3}, 4 x 10^{-3}, the specimen was broken by applied positive force.

2. Method of measurement

(1) Liner
The strain of the liner plate was measured with strain gauges.
The liner anchor's out-of-plane displacement was measured with displacement gauges.
The liner plate condition was observed visually, and recorded by sketches and photographs.

(2) Concrete section
The horizontal displacement of the loading point and the vertical relative displacement in the flange surface were measured with displacement gauges.

Strain on the steel reinforcement was measured with strain gauges. The axial pushing force by the tendon and PC steel rod were measured with load cells. Cracks in the concrete surface were observed visually and recorded by sketches and photographs.

TEST RESULTS

1. Progress of the test

The relationship between the shear force and displacement of each specimen is shown in Fig. 4. Bend induced cracking of the flange was noted in every specimen and the ultimate strength was reached during bend induced crack of the flange, shear induced cracking of the web, yielding of the liner plate and tensile yielding of the flange in a vertical direction. Force was then applied to a member with a cross section of approx. 10^{-2} and then released. However no catastrophic failure, such as a sudden drop in load, arose before the ultimate strength was gained and beyond that until the completion of stress release after the maximum deflection was recorded. The condition of the concrete surface and liner surface of the web at the end of the test is shown in Fig. 5. In the concrete portion of the specimen it was noted that shear sliding occurred near the boundary where the originally closely spaced steel reinforcement becomes more openly spaced. In the liner a large number of bulges were observed at an angle of approximately 45° to the direction of the liner anchor. However there was no indication of the liner pulling away from the concrete at the anchor location or damage to the liner where it is fixed in position.

Fig. 6 shows crack of the concrete in a horizontal cross section where shear sliding took place at the web of each specimen.

In every specimen, crack occurred in the concrete extending continuously along the curved surface of the concrete from the tip of the flange of the liner anchor to the adjacent anchor.

Similarly, continuous crack along the curved surface of the concrete occurred at the position of the external reinforcement.

Table 3 shows the loads and horizontal deflections which caused the various phenomena.

In each specimen, the ultimate strength was reached at a load approx. 3.5 times the load corresponding to the S2 earthquake.

2. Relationship between shear stress (τ) and shear strain (γ)

Fig. 7 shows the relationship between shear stress (τ) and shear strain (γ) for each specimen. The diagram compares shear strain (γ_1), obtained by subtracting bending displacement from the total displacement, with shear displacement (γ_2, γ_3), obtained from readings of displacement gauges located on the concrete side and the liner side of the center of the web.

The $\tau-\gamma$ relationships obtained by each of these three methods are approximately the same, confirming the monolithic behavior of the liner system and concrete.

3. Liner plate shear force sharing behavior

Fig. 8 shows how the shear force of liner-plate is shared at the time of loading for the center of the upper liner panel of each specimen (the A-line) and the center of the lower liner panel where concrete shear slip occurs at the time of maximum load (B-line).

As this figure shows, in each specimen the shear force is shared, from the initial stress phase through the stress phase where shear cracks occurred in the wall concrete to the yield of the liner plate.

Because specimen W-8-8 uses a liner plate with a thickness only half that of the other specimens, its share of the shear force is also only half that of the other specimens. Also, the liner plate of specimen W-10-4 yielded at a higher stress than that of the other specimens because its liner plate's yield strength was greater than that of the other specimens.

4. Surface displacement of the liner anchor

Fig. 9 concerns the W-10-4 specimen and shows the out-of-plane displacement of the vertical liner anchor with respect to shear stress.

The measured out-of-plane displacement position is in the vicinity of the position where shear sliding failure occurred in the concrete under the web at the time of ultimate strength.

As shown in the figure, beyond the shear stress stage ($\tau =$ about 60 kg/cm^2), where shear crack occurred at the surface of concrete at the center of the horizontal surface of the web, the out-of-plane displacement gradually increased in value as the loading was increased. The displacement increased rapidly just before the maximum strength was reached.

CONCLUSIONS

The following conclusions could be drawn from the results of the tests.

(1) For each specimen there was scarcely any noticeable difference with regard to Q–δ relationship and/or $\tau-\gamma$ relationship; such minor differences are not expected to significantly influence the behavior of any part of the PCCV if they are within the range of the liner anchor scale factor and the curvature of the concrete wall.

(2) The $\tau-\gamma$ relationship displayed by each specimen and transitional behavior of the liner plate with regard to sharing the shear forces, indicate that the liner plate follows the concrete wall and shares the load even when concrete behaves non–linearly.

(3) Although a large number of bulges appeared diagonally toward the liner plate with the liner anchor position in the liner portion as the boundary border, no marked pulling–out of the liner plate (including the liner anchor) from the concrete body was noticeable, nor any damage at the fixed end in the vicinity of liner. When the specimen's horizontal cross–section was observed after the test, however, roughly continuous cracks were noted along the liner plate in the anchor flange position of the concrete part.

(4) Each specimen reached its maximum strength at a load approximately 3.5 times the load corresponding to the S2 earthquake.

From the above results, we believe that the present test confirmed that the efforts to modernize the individual components of the seismic proving test model are reasonable. Furthermore, this test afforded valuable data for evaluation of each part of the seismic proving test, and for appraisal of the actual PCCV.

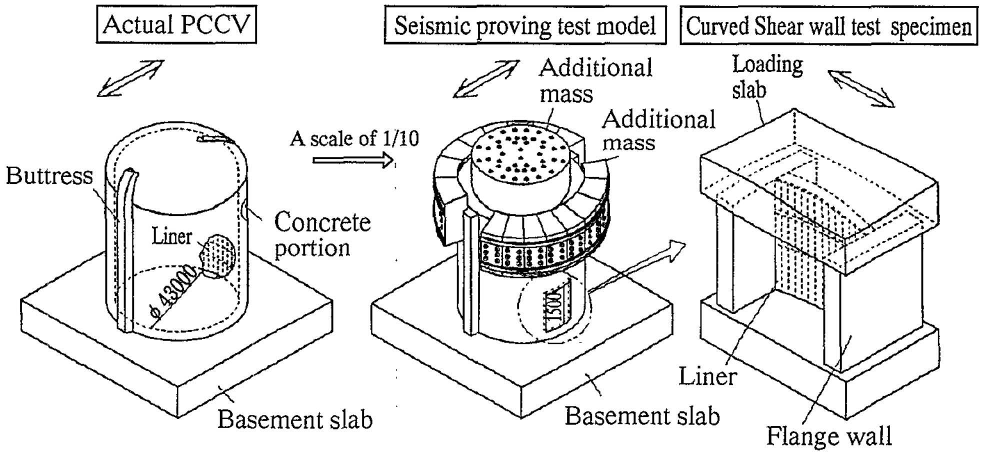


Fig.1 Modeling portion of the curved shear wall test specimen

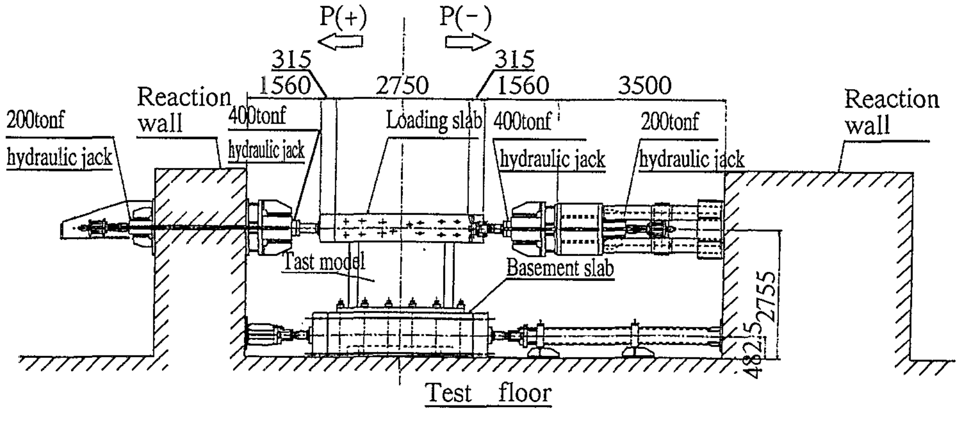
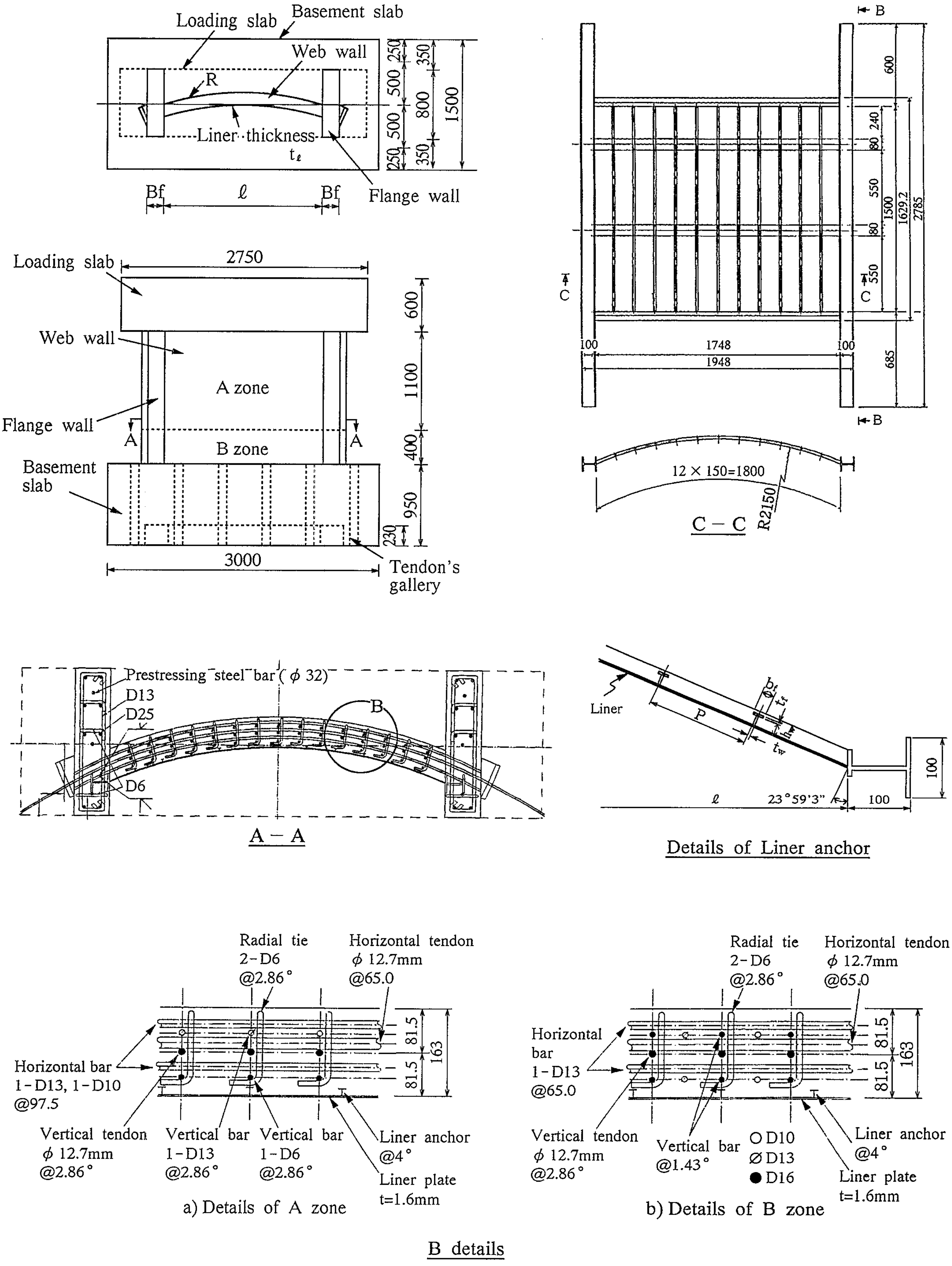


Fig.3 Loading system

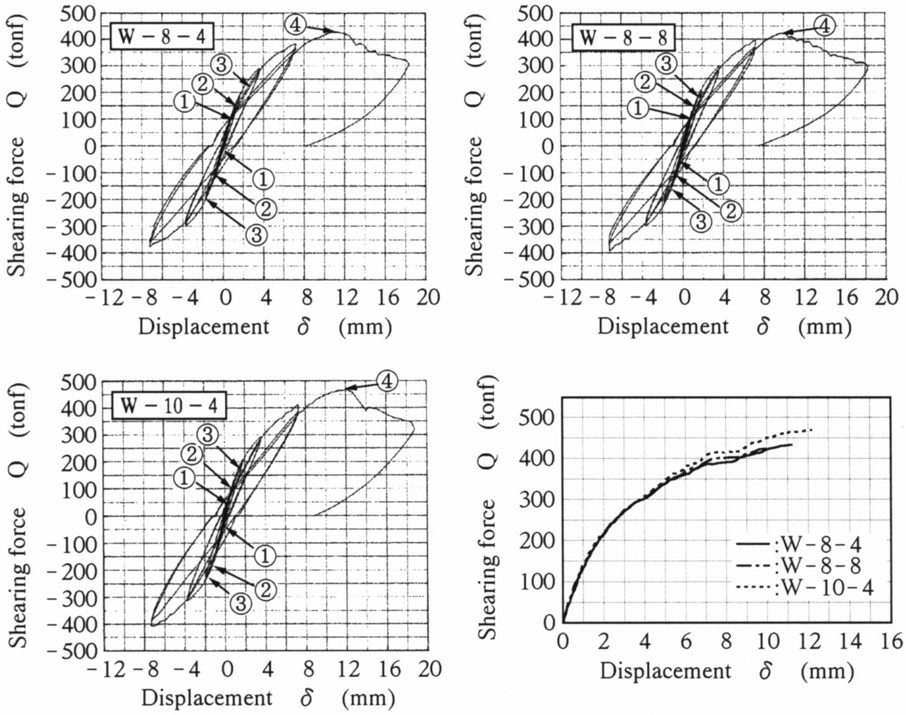


a) Details of A zone

b) Details of B zone

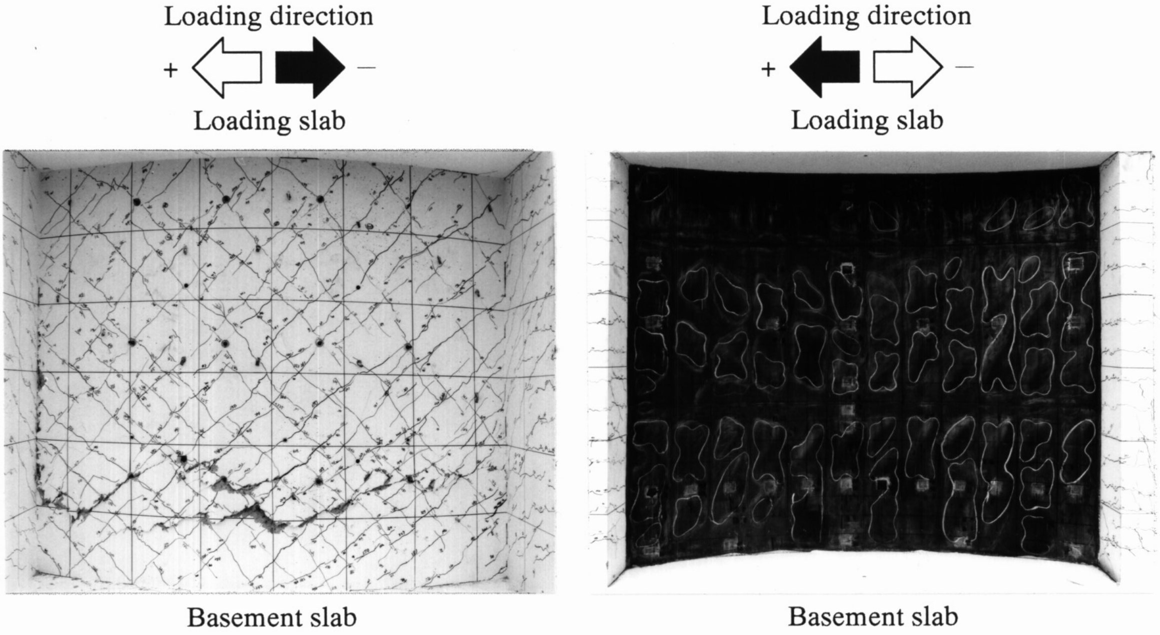
B details

Fig.2 Details of test specimen (W − 10 − 4)



① Bending crack at flange wall leg ② Shearing crack at web wall corner
③ Shearing crack at web wall center ④ Maximum load

Fig.4 Relationship between shearing force (Q) and displacement (δ)



a) Concrete surface b) Liner surface

Fig.5 Ultimate state of surface (W － 10 － 4)

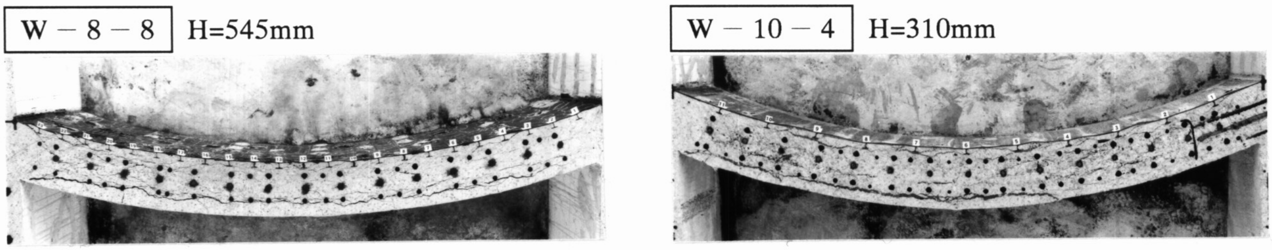


Fig.6 Ultimate state of cutted horizontal section

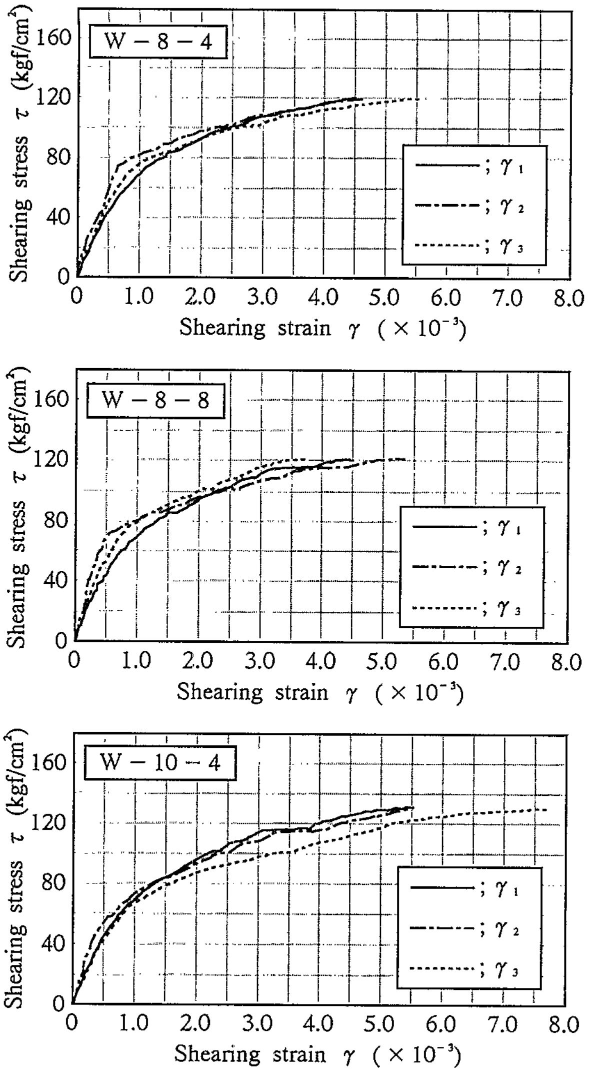


Fig.7 Relationship between shearing stress and shearing strain

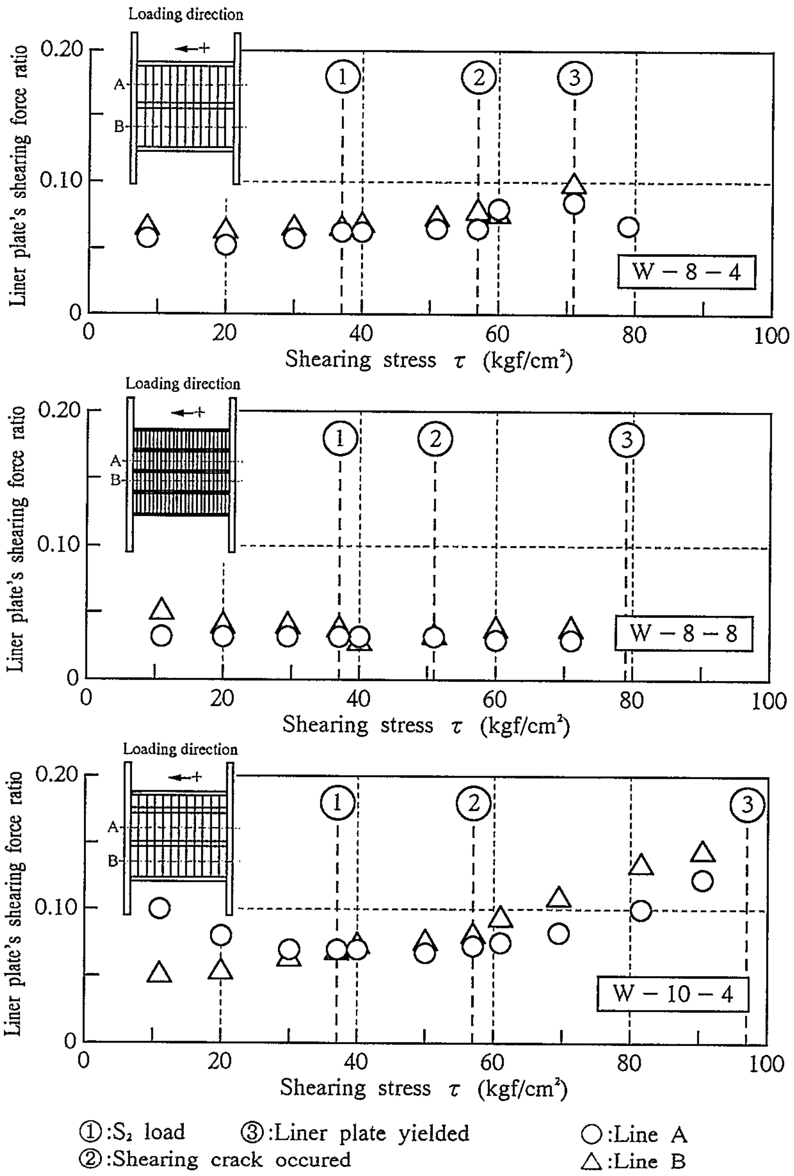
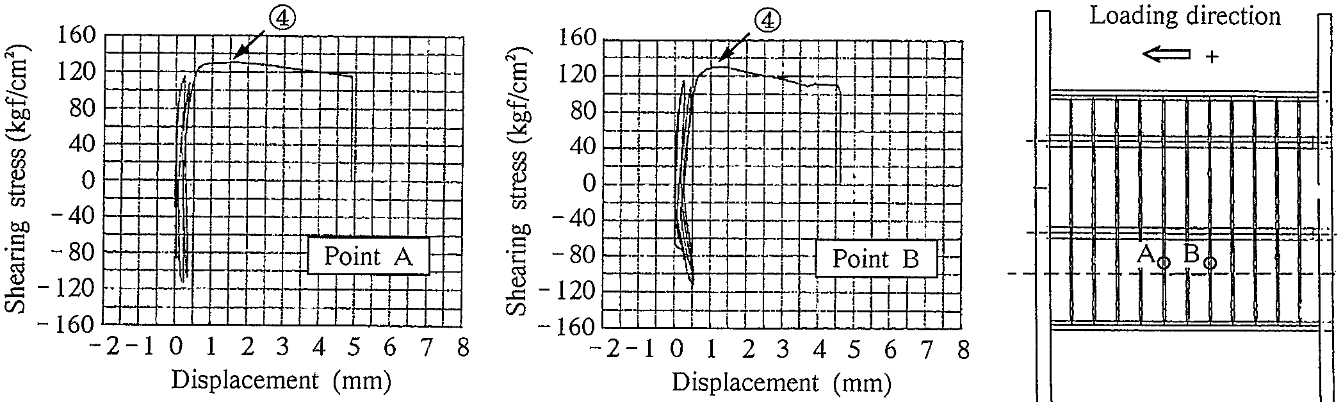


Fig.8 Liner plate's shearing force ratio to total shearing force



Note ; ④shows maximum load

Fig.9 Out-of-plane displacement of vertical liner anchor (W − 10 − 4)

Table 1. Test specimens

* Test specimen	Scale						Each part dimension								
											Vertical liner anchor				
	Web thickness	Web curvature	Liner system thickness	Vertical liner anchor web's height and flange's width	Horizontal liner anchor web's height	Vertical liner anchor space	Web curvature radius R	Liner thickness t_ℓ	Web inside length ℓ	Flange thickness B_f	Web thickness t_w	Flange thickness t_f	Web's height h_w	Flange's width b_f	Space P
W-8-4	1/8	1/8	1/4	1/8	1/8	1/4	2850	1.6	1767	175	1.6	2.3	13.7	18	150
W-8-8	1/8	1/8	1/8	1/8	1/8	1/8	2850	0.8	1767	175	0.8	1.2	14.8	18	75
W-8-10	1/8	1/10	1/4	1/8	1/8	1/4	2313	1.6	1747	185	1.6	2.3	13.7	18	150

* Test specimens name ; W – 10 – 4

Wall ↑ (W) ; ↑ (10) Scale of web wall curvature ; ↑ (4) Scale of liner system thickness

Table 2. Material test results of concrete and liner plate

Value		Test specimen		
		W – 8 – 4	W – 8 – 8	W – 10 – 4
Concrete	Compressive strength (kgf/cm^2)	477	544	401
	Splitting tens. strength (kgf/cm^2)	36.1	34.3	35.4
	Modulus of elasticity (× 10^5) (kgf/cm^2)	2.60	2.72	2.37
	Poisson's ratio	0.195	0.191	0.177
Liner plate	Material Plate thickness (mm)	SPCC 1.6	SPCC 0.8	SGV410 1.6
	Yield strength (kgf/cm^2)	1910	1740	3530
	Tensile strength (kgf/cm^2)	3220	3230	5200
	Modulus of elasticity (× 10^6) (kgf/cm^2)	2.19	2.19	2.23
	Elongation (%)	45.8	50.0	33.9

Table 3. Summary of test results

Value			Test specimen					
			W – 8 – 4		W – 8 – 8		W – 10 – 4	
Bending crack	Q_{bc} (tonf)	τ_{bc} (kgf/cm^2)	81.8	23.2	102.4	29.0	60.0	16.7
	δ_{bc} (mm)	R_{bc} (× 10^{-3})	0.55	0.31	0.64	0.35	0.38	0.21
Shearing crack	Q_{sc} (tonf)	τ_{sc} (kgf/cm^2)	200.0	56.7	180.1	51.0	207.1	57.5
	δ_{sc} (mm)	R_{sc} (× 10^{-3})	1.79	0.99	1.44	0.80	1.77	0.98
Liner plate yield	Q_{Ly} (tonf)	τ_{Ly} (kgf/cm^2)	249.6	70.7	279.1	79.1	349.3	97.0
	δ_{Ly} (mm)	R_{Ly} (× 10^{-3})	2.60	1.44	3.11	1.73	5.13	2.85
Flange vertical bar yield	Q_{by} (tonf)	τ_{by} (kgf/cm^2)	405.2	114.8	404.4	114.6	405.2	112.6
	δ_{by} (mm)	R_{by} (× 10^{-3})	9.30	5.17	8.60	4.78	7.06	3.92
Maximum load	Q_{max} (tonf)	τ_{max} (kgf/cm^2)	428.3	121.3	423.2	119.9	468.4	130.1
	δ_{max} (mm)	R_{max} (× 10^{-3})	11.18	6.21	9.85	5.47	12.15	6.75

Q ; Shearing force　τ ; Shearing stress (= Q/A_ω)

A_ω ; W-8-4, W-8-8 ; 3530cm^2

W-10-4 ; 3600cm^2

δ ; Displacement　R ; Displacement angle (= δ /h)

h ; Loading hight