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Seismic proving test of concrete containment vessels. The evaluation of the test results on curved shear walls with liner for the PCCV test model

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ABSTRACT

Since 1980 a series of seismic proving tests of nuclear power facilities have 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 the overall program, NUPEC has planned to perform seismic proving test for a PWR prestressed concrete containment vessel(PCCV) since 1992.

The objectives of the test are to prove the structural and functional integrity of a PCCV subjected to earthquakes. This report describes the test results and analytical evaluation of curved shear walls for the PCCV, as one of the auxiliary tests for the PCCV. We have already reported the test results on the curved shear walls subjected to static alternate loading. [1]

This test was conducted in order to confirm the adequacy of the PCCV test model, which has the different scales between 1/10 as PCCV whole geometry, 1/8 as concrete wall thickness and 1/4 as liner plate thickness.

KEYWORD

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

PURPOSE OF THE TEST

The lower portion 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 concrete cylinder wall 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, while the concrete potion of the seismic proving test model was made to a scale of 1/10. The scale factors for the height of the web and the width of the flange of the liner anchor were fixed at 1/8 to avoid interference with the reinforcing bars and tendons 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 differ from that 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 hold the liner to the concrete wall when the behavior of the concrete is inelastic.

Fig. − 1 shows a comparison of the PCCV shear wall test specimens used in this experiment with the actual PCCV structure and the seismic proving test model.

SPECIMENS

Table− 2 shows the specifications of specimens used in the test. The loading apparatus is shown in Fig. − 2. Fig. − 3 gives a detailed description of the test model. Three 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. The M/QD (shear span ratio) of these specimens is 0. 85 (nearly equal to that of the seismic proving test model).

Table− 3 shows the material test results of concrete and liner plate, and Table− 4 shows the test results of the curved shear wall test specimens subjected to static alternate loading .

TEST METHOD

1. Method of applying force

Horizontal force was applied to the specimen with the basemat fixed to the test floor.

Horizontal force was applied alternately by hydraulic jacks. The center of loading slab was aligned with that of rigidity when the wall was elastic.

Prior to applying the horizontal load, prestressing forces (circumferential : 79. 5 kgf/cm2, vertical: 79. 0 kgf/cm2) equivalent to those of the actual structure were applied to the specimen. The forces of seismic loads S1 and S2 were applied two times each in positive and negative direction.

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 portion

The horizontal displacement of the loading point and the vertical relative displacement in the flange surface were measured with displacement gauges.

The strain of the reinforcing bars was measured with strain gauges. The axial force by the tendon and PC steel rod were measured with load cells.

Cracks on the concrete surface were observed visually and recorded by sketches and photographs.

ANALYSIS MODEL

Two types of analysis model are adopted. One is the beam model that is the simplified single mass model, and the other is the FEM model. Fig. – 4 shows the FEM analytical model and Fig. – 5 shows the concept of beam model.

In beam model, the horizontal total displacement is assumed to be the sum of the three modes which are the deformation and the rotation due to bending moment and deformation due to shear force.

The FEM model is performed on the full size specimen using shell elements. The concrete portion is modeled by the laminated shell elements and the liner plate is modeled by shell element.

The $\sigma - \varepsilon$ relationships proposed by Naganuma [2] were applied in the analysis.

TEST AND EVALUATION RESULTS

1. Progress of the test

Bending-induced cracking at the flange was found and the ultimate strength was attained after yielding of the liner plate and tensile yielding of the flange in vertical direction.

However, no catastrophic failure, such as a sudden drop in the load, arose before the ultimate strength was gained and beyond that until the completion of stress release after the maximum deflection was recorded.

2. Relationships between shear force and displacement

Fig. – 6 shows the comparison of test result and analysis results between shear force (Q) and total displacement (δ) for W– 10– 4 specimen . The total displacement is composed of bending and shear deformation. The FEM analysis shows a little smaller displacement than test result after shear cracks occurred . This is assumed that the FEM model had no consideration of the rotation deformation due to the slipping out of vertical rebars from the basemat. Table 1 indicates the ultimate strength agreed well with both analyses and test result.

3. Crack patterns and the ultimate failure mode

The condition of concrete cracks are shown on Fig. – 7. In the end of the test, the shear sliding failure in the concrete portion of specimen is expected to occur at the bottom near the basemat. The FEM calculation shows a good agreement with test result .

4. Supporting ratio of liner plate

Fig. – 8 shows to what extent the liner plate supports the total shear force both at the center of the upper liner panel (location A) and at the center of the lower liner panel (location B) where concrete shear failure occurs at the time of maximum load application .

Based on this figure , the liner plate shared the shear force from the initial stress status through the maximum load. Because the specimen W– 8– 8 uses a liner plate with a thickness only half that of W– 8– 4, its share of shear force is only half and the supporting ratio change is small. The nonlinear analysis can trace the supporting ratio changes of liner plate. The ratio increases after the shear cracks and decreases after the yielding of liner plate. The FEM analysis agrees well with the test results.

5. Modeling appropriateness for liner anchors based on the preceding tests

The relationships of shear force and shear deformation with or without considering springs which correspond to liner anchors is compared in Fig. -9. There is no difference between the two curves . This implies that in modeling of liner anchors , liner and concrete exhibits same behaviors, so that liner anchors are not necessarily modeled by springs .

CONCLUSIONS

The following conclusions could be drawn from the test results and the evaluations.

(1) The test results show no marked pulling-out of the liner plate including liner anchors from the concrete wall was noticeable, nor any damage at the fixed end in the vicinity of liner anchors. This means concrete portion and liners behave the same until the ultimate state .

(2) The FEM model which assumes the deformation of concrete and liner shows good agreement with test results.

(3) The simplified beam model could be alternatively applied for this type of system where shear deformation dominates .

REFERENCE

[1] NAKAMURA, S 1996 Seismic proving test of concrete containment vessels Part1: Model tests of a curved shear wall for the PCCV Proc. 11th WCEE, poster-1799 , Mexico

[2]NAGANUMA, K 1991 An Analytical Model of Reinforced Concrete Panel under In-Plane Shear Stress SMiRT 11 Transactions vol. H , Tokyo, Japan

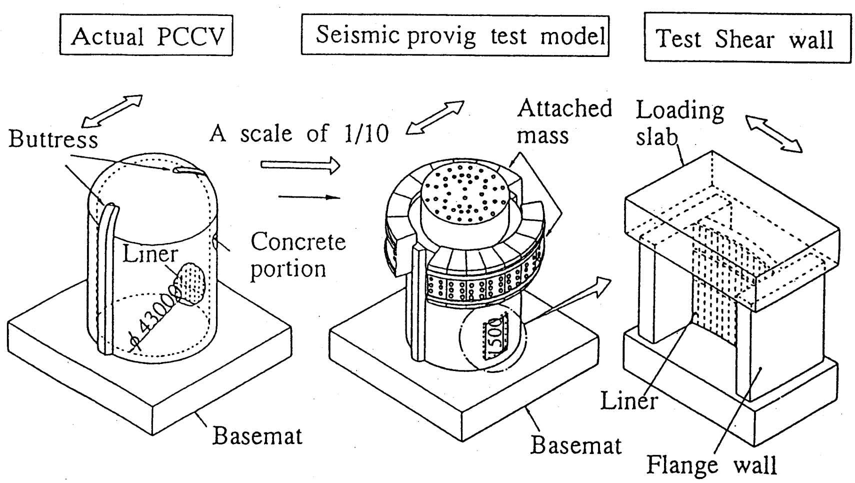

Fig. 1 Modeling portion of the curved shear wall test specimen

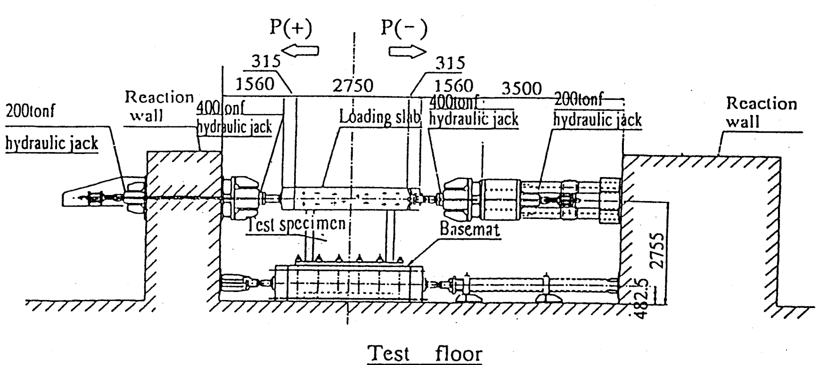

Fig. 2 Loading system

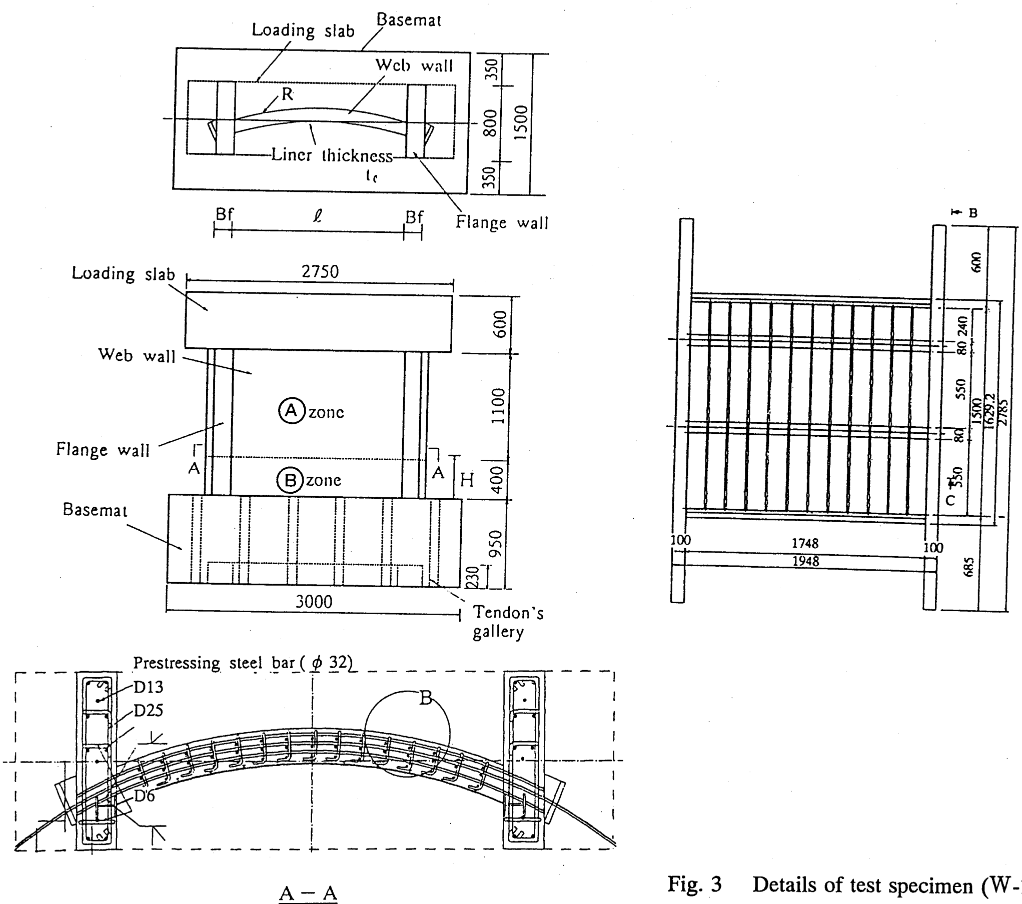

Fig. 3 Details of test specimen (W-10-4)

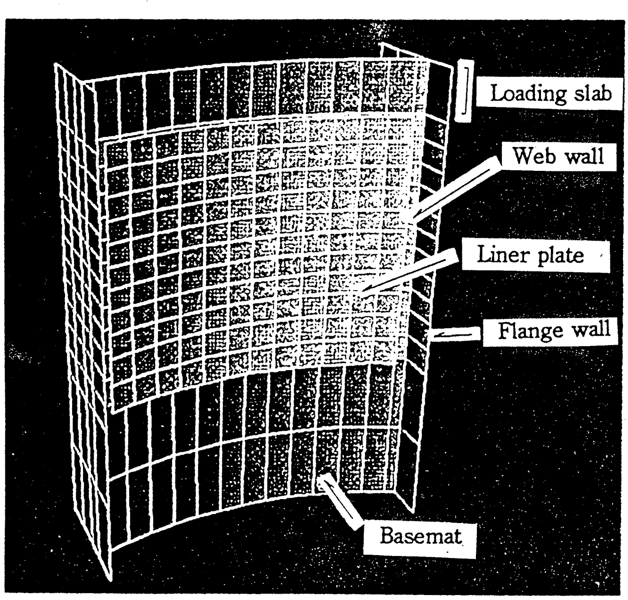

Fig. 4 FEM analytical model

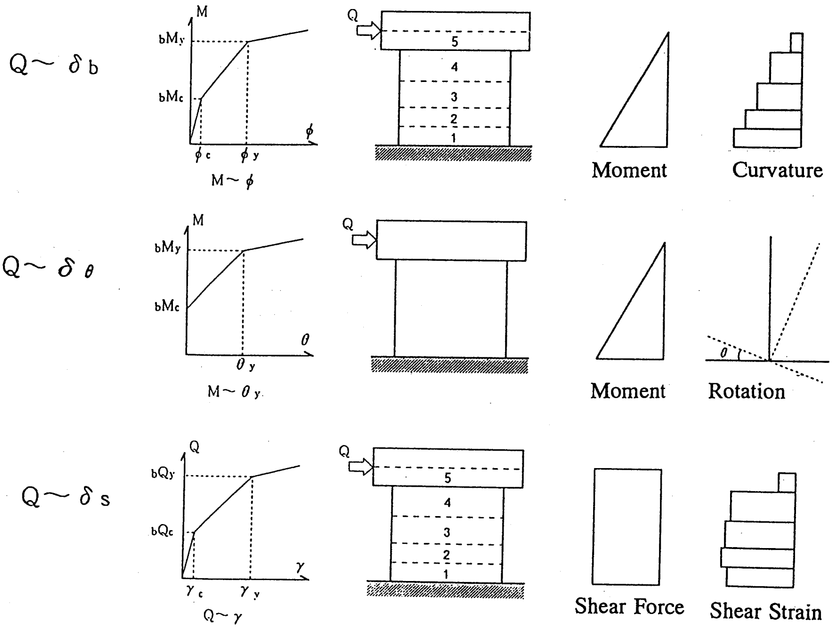

Fig .5 Concept of beam model

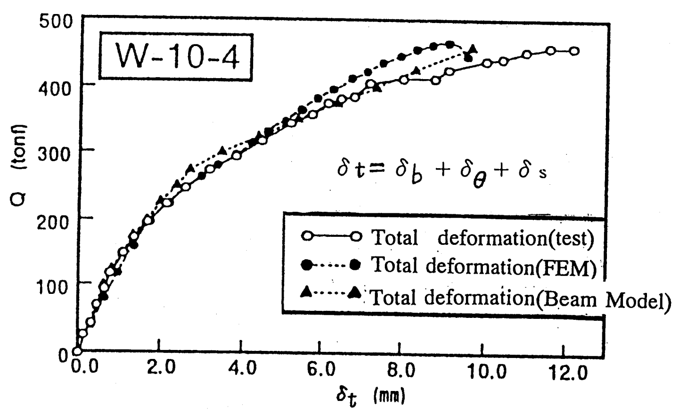

Fig. 6 Comparison of total displacement between test and analyses

Table 1 Comparison of ultimate strength

	Test Qe (tonf)	FEM Qf (tonf)	Beam model Qb (tonf)	Qe/Qf	Qe/Qb
W-8-4	428	488	459	0.88	0.93
W-8-8	423	523	441	0.81	0.96
W-10-4	468	466	460	1.00	1.02

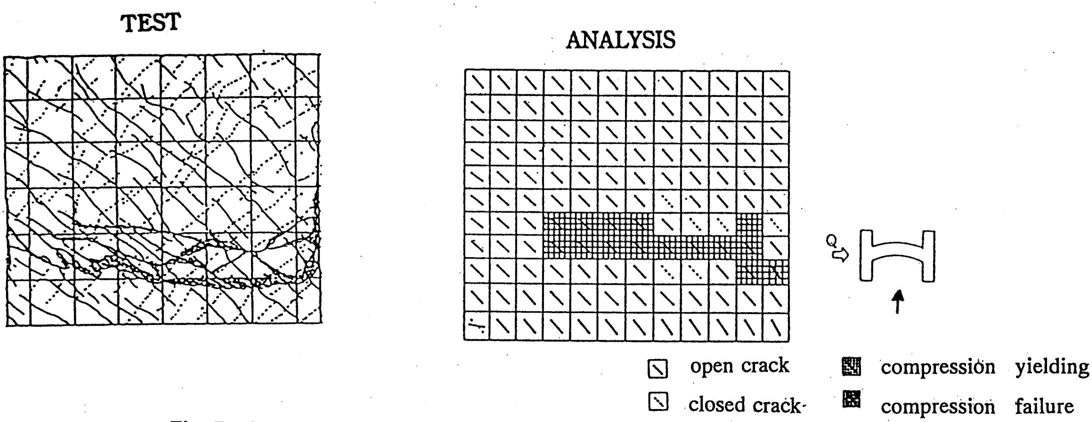

Fig. 7 Comparison of ultimate failure mode

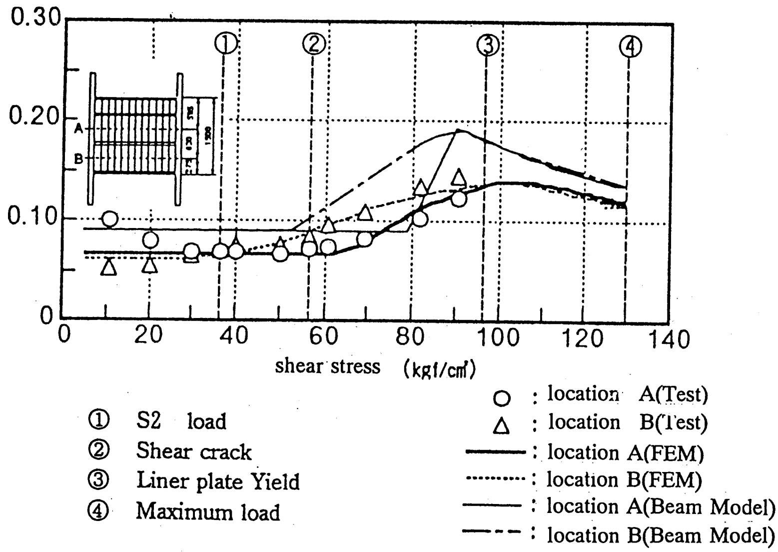

Fig. 8 Supporting ratio of liner plate for shear force

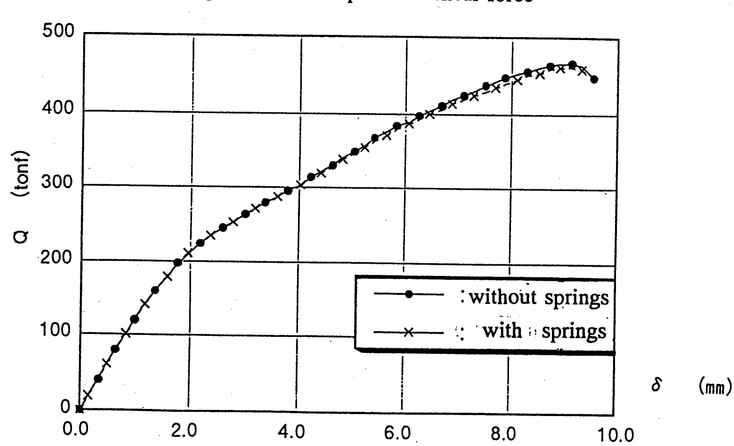

Fig. 9 Relationships of shear force and shear deformation with or without considering springs due to liner anchors

Table 2 Test specimens

Test specimen*	Scale						Each part dimension								
	Web thickness	Web curvature	Liner system thickness	Vertical liner anchor web height and flange width	Horizontal liner anchor web height	Vertical liner anchor spacing	Web curvature radius R	Liner thickness t_l	Web inside length ℓ	Flange thickness B_f	Vertical liner anchor: Web thickness t_w	Vertical liner anchor: Flange thickness t_f	Vertical liner anchor: Web height h_w	Vertical liner anchor: Flange width b_f	Vertical liner anchor: Spacing 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-10-4	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) — Scale of web wall curvature (10) — Scale of liner system thickness (4)

Table 3 Material properties of concrete and liner plate

Items		Test specimen W-8-4	Test specimen W-8-8	Test specimen W-10-4
Concrete	Compressive strength (kgf/cm^2)	477	544	401
	Tensile (Splitting) strength (kgf/cm^2)	36.1	34.3	35.4
	Modulus of elasticity ($\times 10^5$) (kgf/cm^2)	2.60	2.72	2.37
	Poisson 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 ($\times 10^6$) (kgf/cm^2)	2.19	2.19	2.23
	Elongation (%)	45.8	50.0	33.9

Table 4 Summary of test results

Items			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} ($\times 10^{-3}$)	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} ($\times 10^{-3}$)	1.79	0.99	1.44	0.80	1.77	0.98
Liner plate yielding	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} ($\times 10^{-3}$)	2.60	1.44	3.11	1.73	5.13	2.85
Vertical flange rebar yielding	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} ($\times 10^{-3}$)	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} ($\times 10^{-3}$)	11.18	6.21	9.85	5.47	12.15	6.75

Q ; Shearing force τ ; Shearing stress ($= Q/A_w$)

A_w ; W-8-4, W-8-8 ; $3530cm^2$

W-10-4 ; $3600cm^2$

δ ; Displacement R ; Displacement angle ($= \delta / h$)

h ; Loading hight