Experimental Study on RCCV of ABWR Plant
Part 4: Experiment on Joint of Diaphragm Floor

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1. INTRODUCTION

In the trial design of RCCV, the diaphragm floor (hereinafter abbreviated as "D/F") which divides the inner space of RCCV into two parts is rigidly connected to the cylindrical wall. Between the D/F and the wall this joint is interposed by steel liner supplied inside the wall for securing air-tightness (see Ref. 1 and Fig. 1).

As the critical load, at the differential pressure test of RCCV the out-of-plane shear force acts on the D/F by the differential pressure of the two parts in the RCCV combined with the tensile force caused by the inner pressure on the cylindrical wall. In the design, the membrane and flexural tensile forces in the D/F are supposed to be transferred to the wall by reinforcing bars through couplers welded on the either surface of the liner, and the out-of-plane shear force is by shear plates welded on the liner. The objective of this experiment is to clarify the shear transfer properties and the strength of the joint, and to evaluate the adequacy of the trial design.

2. SPECIMENS

For specimens, the shaded portion shown in Fig.2 was modeled as a assemblage of the two plane plates. The scale of the specimens is approximately 1/3. For the experimental parameters, the shear span ratio a/D, with and without shear plates and the dowel action of the couplers were adopted and four specimens were used.

Table 1 shows a summary of the specimen types. Fig.3 shows the geometrical configuration of the specimens and Fig.4 shows the detail of the joint.

For the specimen whose dowel effect of the couplers was eliminated, no coupler was used. The longitudinal reinforcing bars were placed through small holes in the liner plate and,cushion material of the same length as the couplers was wound around the bars (Fig.5).

3. TEST PROCEDURE

Fig.6 shows the loading apparatus. The loading procedure is shown in Fig.7. At the first step, the axial tensile stress equivalent to that at the Structural Integrity Test (SIT) was applied to the D/F. After unloading it, out-of-plane shear force was increased under the constant tensile stress equivalent to that at the differential pressure test.

The out-of-plane displacement of the D/F and the slippage between the D/F and the cylindrical wall were measured. Strain of reinforcing bars, shear plates, liner and couplers were measured by electric wire strain gauges.

4. TEST RESULTS AND DISCUSSION

4.1 Mechanical Properties of the Material

The mechanical properties of concrete, reinforcing bars, the steel plates used for the liner and shear plates are summarized in Table 2, 3 and 4 respectively.

4.2 Axial Tensile Force Loading Experiment

At the first step, axial tensile stress equivalent to that at the SIT (average stress =10kgf/cm^2) was loaded to the D/F. No visible cracks occurred in the specimens in this experiment. The distribution of strain of the longitudinal reinforcing bars of the D/F are shown in Fig.8. The strain was found to be below the allowable stress for all the specimens. The strain of reinforcing bars is larger in near the joint of the D/F and the wall. This is attributable to the fact that the tensile force in concrete of the D/F is transferred to the bars in the vicinity of the joint face and anchored in the wall through the couplers.

4.3 Loading Out-of-plane Shear Force under Constant Axial Tensile Force Experiment

Out-of-plane shear force was loaded to the D/F up to failure under the constant axial tensile stress (5kgf/cm^2) equivalent to that at the differential pressure test.

a. Crack and Failure Pattern

The ultimate failure pattern of each specimen is shown in Fig.9. For all the specimens, the predominant failure pattern was shear-compression failure of the D/F.

In Specimen A-1, the initial crack was found at the vicinity of the upper shear plate in the D/F and near the upper coupler in the wall. After that, a diagonal crack at the D/F was found at the shear force Q=180tf, and also the yielding of the longitudinal top reinforcing bar in the D/F began. At Q=210tf concrete crushed in the vicinity of the lower shear plate in the D/F. In Specimen A-2, after the formation of flexural cracks and diagonal cracks in the web of D/F, concrete crushed at the maximum shear force Q=118tf. In Specimen B-1, with no shear plate, diagonal crack at the D/F was caused at Q=80tf and extended up to near the liner. The longitudinal top reinforcing bars yielded at Q=185tf and then concrete crushed in flexure-compression zone. In Specimen C-1, with the dowel effect of the couplers eliminated, after crushing of concrete in the same manner with A-1, bond splitting cracks along top reinforcing bars were continued to the diagonal cracks.

b. Strength

Table 5 shows the strength in the experiment as compared with the calculated values. An evaluation for the maximum shear force is shown in Table 6.

For Specimens A-1 and C-1 which had shear plates, the value $\tau u/\sqrt{Fc}$ (τu : average shear stress of the D/F under the maximum shear force, Fc : compressive strength of concrete) was 4.0, with no difference between the two. This shows that the strength for shear transfer between the D/F and the wall is higher than that of D/F member even if the dowel effect of the coupler is eliminated.

The value of $\tau u/\sqrt{Fc}$ without shear plates (B-1) is about 90% of that with shear plates. This difference is considered to be caused by also confined effect of shear plates in the flexure-compression zone.

The ratio of the maximum shear force in the experiment to the calculated ultimate shear strength as a beam by a proposed formula ranged 1.1 to 1.4, indicating a considerable difference. However, this is within the range that the formula is applicable.

For all the specimens, the maximum shear force in the experiment was determined by that of the D/F member, and the strength for shear transfer between the D/F and the wall was higher than that of the D/F member.

In table 6 estimated maximum shear force $Q_u^{\blacktriangledown}$ at the compressive concrete strength Fc=300kgf/cm^2 (specified strength) is shown. Fig. 10 shows the relation between $Q_u^{\blacktriangledown}$ and the shear span ratio. The ratio of $Q_u^{\blacktriangledown}$ to the shear force equivalent to that at the differential pressure test is 3.7 at a/D=1.2, and 6.8 ~ 7.8 at a/D=0.6, indicating to have sufficient safety.

c. Out-of-plane Displacement of the D/F

Fig. 11 shows the relation between the shear force (Q) and the relative out-of-plane displacement (δ) to the wall joint at the loading point of the D/F in the case of a/D=0.6. For specimen A-1 and C-1 which have shear plates those Q-δ relation are nearly same, whereas for specimen B-1, with no shear plate, the displacement is larger. This shows the shear plates increase the rigidity of the member. And, the displacement δ at the maximum load is almost the same for the specimens with shear plates regardless of the presence of dowel effect of the couplers, but is about 60% of the former for specimen B-1 (without shear plates).

d. Slippage between the D/F and the Wall

Fig. 12 shows the relation of the shear force versus measured relative slippage between the D/F and the wall. Among the three specimens of a/D=0.6, the slippage of the specimens without shear plates or without dowel effect of couplers is slightly larger than that of specimen A-1 which has those under the lower load. Under the higher load, the slippage of B-1 is larger than that of other two specimens. As for the slippage under the shear force equivalent to the differential pressure test (Q_D=27.5tf), it is 0.03~0.04mm for the trial design model (A-1, A-2), and under 0.1mm for all the specimens, which are very small values.

e. Strain of Reinforcing Bar

The relation between the shear force (Q) applied to the D/F and the measured stain of the longitudinal reinforcing bars is shown in Fig. 13. At the load equivalent to the differential pressure test, the strain was found to be below the allowable stress for all the specimens.

The strain of the bottom reinforcing bars in the specimens of a/D =0.6, increases in compression according as the increase of the shear force in the lower load, but during the range of the shear force 90tf ~140tf it turns to tensile strain. This change is considered to be caused by that of the load transfer mechanism in company with the crack propagation, and under the higher load the tensile strain due to shear transfer becomes predominant in also the bottom bars in the D/F.

5. CONCLUSION

For all the specimens, the maximum force in the experiment was determined by the strength of the D/F member, and the strength for shear transfer between the D/F and the cylindrical wall was higher than that of the D/F member. The joint of the Diaphragm floor to the cylindrical wall of the trial design was approved to be safe enough. The strength was increased by about 10% by the use of shear plate. Also, the shear plate increased the rigidity of the member. In the specimens with the shear plate, the strength and the displacement of the D/F were almost same regardless of the presence of the dowel effect of the couplers.

The design procedure that the transfer of the shear force is supposed to be accomplished only by the shear plates, not taking account of the dowel effect of the couplers brings safe result.

6. ACKNOWLEDGMENT

This study has been carried out as a part of a joint research study on "the Evaluation of the RCCV Configuration and Confirmatory Test to Establish a Code" (Saito et al, 1989).

References

1. Saito,H., Kikuchi,R., Muramatsu,Y., Hiramoto,M., Oyamada,O., Furukawa,H., Sasagawa,K., Omori,N., Suzuki,S., Sugita,M., Kobayashi,I., Yamaguchi,I., (1989). Experimental Study on RCCV of ABWR Plant Part 1 ; Outline of Research Study. Transaction of the 10th SMiRT Conference, Vol.J.

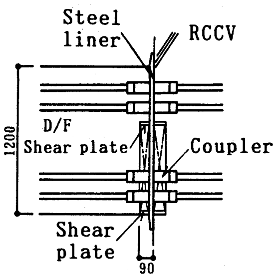
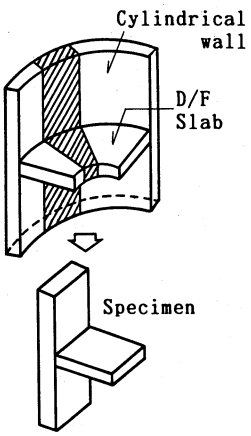


Fig. 1 D/F joint in the trial design



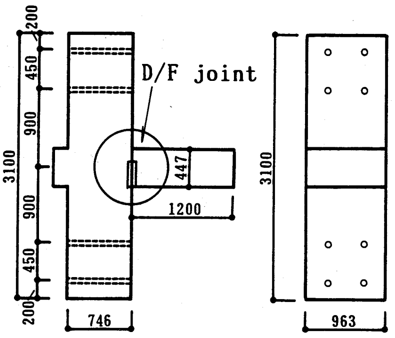


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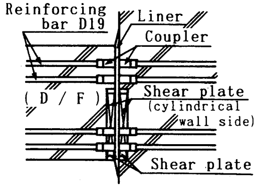
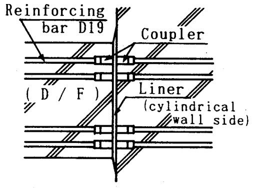
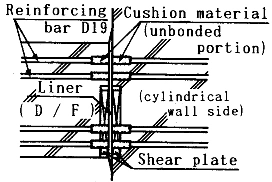
Fig. 2 Modeling of the specimen

Fig. 3 Configuration and dimension of the specimens

Table 1 List of Spesimens

Spec. No.	A - 1	A - 2	B - 1	C - 1
Detail of D/F joint of the specimens	 (Model of trial design)		 (Without shear plate)	 (Without dowel effect of coupler)
Shear span ratio	0.6	1.2	0.6	0.6

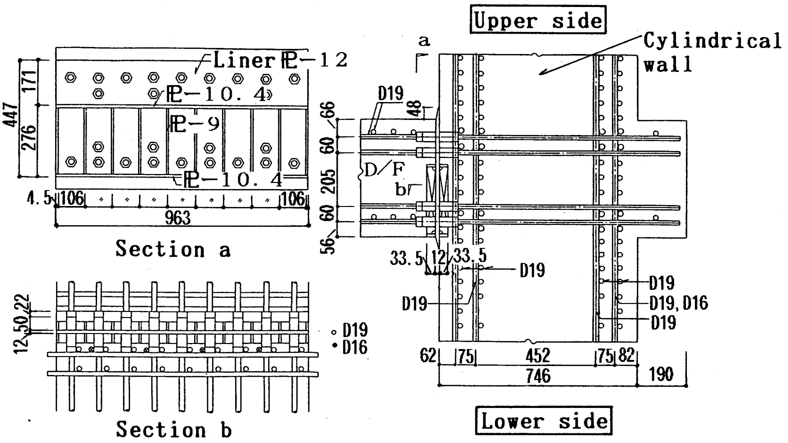


Fig. 4 Joint detail of the specimen (No. A-1, A-2)

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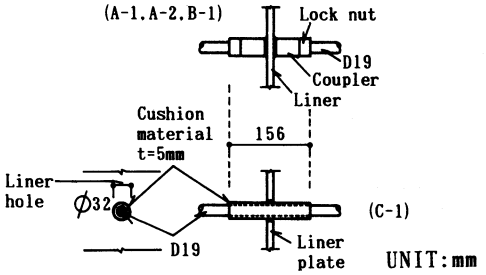


Fig.5 Cushion material around bar (No.C-1)

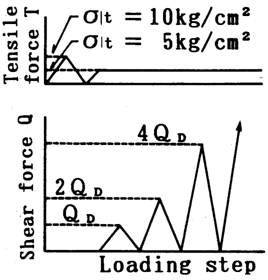


Fig.7 Loading step

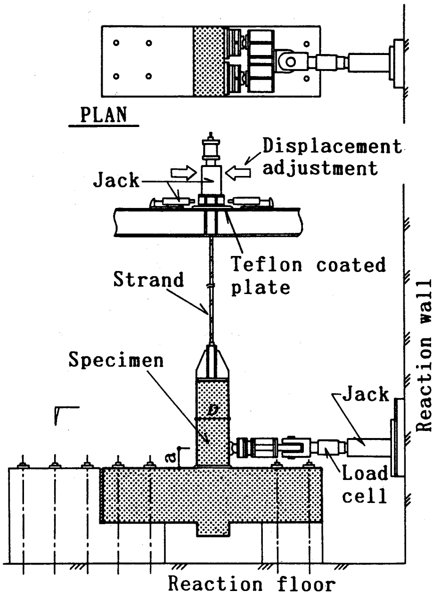


Fig.6 Loading Apparatus

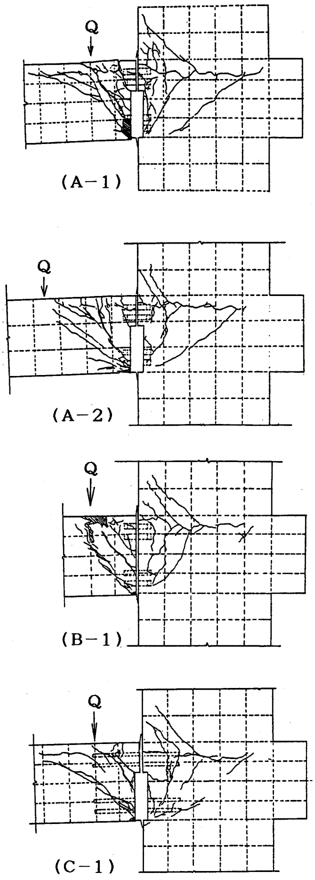


Fig.9 Crack pattern at ultimate

Table 2 Property of Concrete

Spec. No.	Compressive strength Fc kg/cm²	Modulus of elasticity E1/3 10⁵kg/cm²	Tensile strength Ft kg/cm²
A－1	430	3.49	29.7
A－2	410	3.42	29.6
B－1	408	3.61	28.7
C－1	462	3.74	30.5

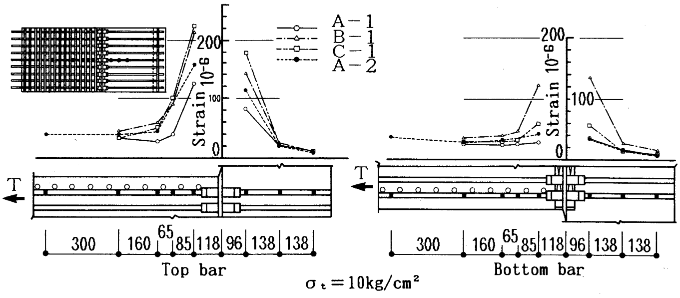
Table 3 Mechanical Property of Reinforcing bar

Diameter	Type	Yield strength σ_y (kg/cm²)	Tensile strength σ_u (kg/cm²)	Elongation (%)
D19	SD35	4,130	6,030	26.1
D16		3,690	5,420	28.0
D10		4,180	5,680	30.8

Table 4 Mechanical Property of Steel Plate

Nominal plate thickness (mm)	Type	Yield strength σ_y (kg/cm²)	Yield point strain 2) ε_y (10^{-6})	Tensile strength σ_u (kg/cm²)	Modulus of elasticity 2) (10^6kg/cm²)	Elongation (%)	Remarks
12	SM50A	4,230	2,060	5,450	2.05	20.3	Liner-use
10.4		4,080	2,010	5,660	2.03	22.5	Shear plate-use
9		3,680	1,820	4,920	2.03	27.7	

Note) 1) Shape and size of test piece are in compliance with JIS Z 2201 No.1 A.
2) Strain gauge measurement values.



$\sigma_t = 10$kg/cm²

Fig.8 Strain distribution of longitudinal bar in D/F

Table 5 Primary result (Strength)

			Strength											
			Experiment value					Calculated value 4)					Experiment value/Calculated value	
			D/F shear force Q (ton), [ ] shows τ (kg/cm²)				⑤ Under max. load $\frac{\tau_u}{\sqrt{F_c}}$	D/F shear force Q (ton)					Flexural yield	Max. load / ultimate shearing strength
Specimen No.	Shear span ratio $^a/_D$	Detail of D/F joint	① Initial crack Q_C	② Start of yielding of rein-forcement Q_Y	③ Crushing of concrete	④ Max. load $Q_U[\tau_U]$		⑥ Flexural crack Q_{FC}	⑦ Shearing crack Q_{SC}	⑧ Flexural yield Q_Y	⑨ Ultimate flexural strength Q_{FU}	⑩ Ultimate shearing strength Q_{SU}	②/⑧	④/⑩
A-1	0.6	Trial design specimen	55	182 162	210	254 [83]	4.00	30	69	182	191	178	1.00	1.43
A-2	1.2		20	109 99	118	119 [39]	1.92	15	52	91	96	104	1.20	1.14
B-1	0.6	Without shear plate	51	185 162	220	220 [72]	3.55	28	68	181	191	172	1.02	1.28
C-1		Without dowel effect of coupler	65	173 185	245	264 [86]	4.02	31	72	182		186	0.95	1.42

Note) 1) Equivalent shear force to that applied during differential pressure test. $Q_D = 27.5$t
2) ②: Yield of top D/F reinforcement in radial direction.
Upper row: D/F side: Lower row: Cylindrical wall side.
3) $\tau = Q/bj$ b: Width of D/F $j = (7/8)d$. d : effective depth of D/F
Fc: Compressive strength of concrete.
4) Calculated for D/F member.
5) ⑦: Ohno/Shibata formula.

$$Q_{sc} = \left(1+\frac{\sigma_o}{150}\right)\left\{0.085\,k_c(500+Fc)/\left(\frac{M}{Q\cdot d}+1.7\right)\right\}b\cdot j$$

6) ⑩: Revised Arakawa formula.

$$Q_{su} = \left\{k_u\cdot k_p\,\frac{0.115(Fc+180)}{M/Q\cdot d+0.12}+2.7\sqrt{P_w\cdot\sigma_{wy}}+0.1\,\sigma_o\right\}b\cdot j$$

Q_{sc}: shear cracking strength (kgf) Q_{su} : ultimate shearing strength (kgf)
σ_o : axial stress (kgf/cm²)
$k_c.k_u$: correction factor according to beam depth. (Architectural Institute of Japan : Standard for Structural Calculation of Reinforced Concrete Structures. 1988)
$k_p = 0.82\times(100\,P_t)^{0.23}$ p_w, σ_{wy}: ratio and yield strength of shear reinforcement, respectively

Table 6 Evaluation of maximum shear force

Speci-men No.	Experimental value $\frac{\tau_u}{\sqrt{Fc}}$	Predicted value for Fc=300kg/cm² τ_u' 1) (kg/cm²)	Q_U' 2) (t)	$\frac{Q'_U}{Q_D}$
A-1	4.00	69.3	212	7.71
A-2	1.92	33.3	102	3.71
B-1	3.55	61.5	188	6.84
C-1	4.02	69.6	213	7.75

Note) 1) $\tau_u' = (\text{Experimental value } \tau_u/\sqrt{Fc})\times\sqrt{300\text{kg/cm}^2}$
2) $Q_u' = \tau_u \times b\cdot j$
3) Q_D : Shear force at differential pressure test

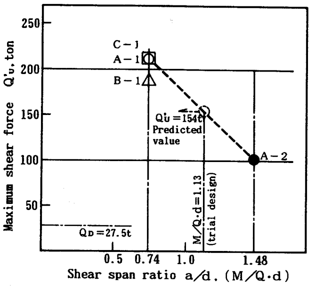


Fig. 10 Maximum shear force VS. Shear span ratio

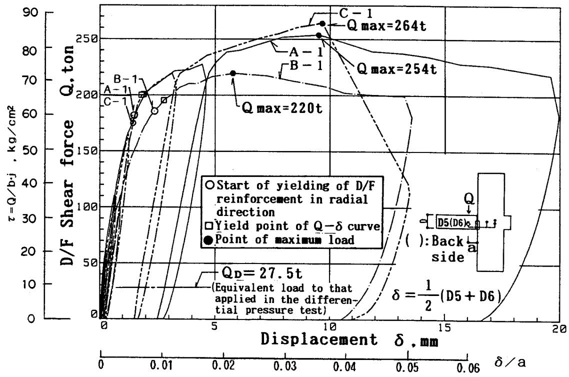


Fig. 11 Relation between shear force Q and displacement δ

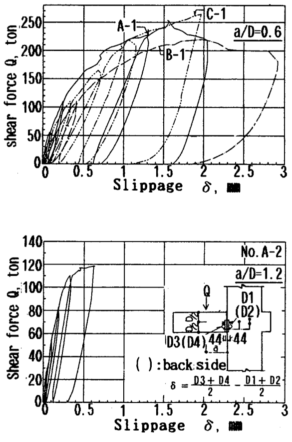
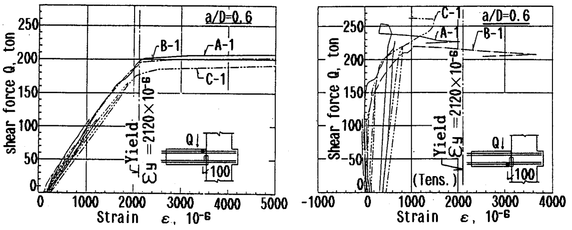


Fig. 12 Shear force VS. slippage between D/F and cylindrical wall



(Top bar) (Bottom bar)

Fig. 13 Relation between shear force and strain of reinforcing bar in D/F