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Experimental Study on Initial Stiffness Degradation and Its Effect on Seismic Capacity of Shear Wall with High Reinforcement Volume Part 3 Static Loading Test on Effect of Drying Shrinkage on Seismic Performance

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ABSTRACT

Seismic response to the Great East Japan Earthquake on March 11, 2011 in the Nuclear Reactor Building of Unit 2 of the Onagawa Nuclear Power Station of Tohoku Electric Power (Onagawa NPP) remained within elastic range, although observation records indicated a little decrease in stiffness. Fine residual cracks were generated in the shear walls of some floors and major factor responsible for the reduced initial stiffness was the impact of ground motion, caused by the Great East Japan Earthquake on March 11, 2011. At the same time, the observation records at Onagawa NPP indicated a slight correlation with deterioration from aging.

The likely factors responsible for deterioration from aging include internal stress, cracks resulting from the drying shrinkage characteristic of concrete and slightly damage caused by micro earthquakes in-service period. Therefore, a static loading test (Static Loading Test [2]) was conducted to investigate the effect of drying shrinkage on initial stiffness and the ultimate strength.

This paper reports on static loading tests for RC shear walls varied a curing method or drying period and the consideration of the observation record analysis of the reactor building in accordance with the result of the tests.

The test results showed that drying shrinkage affected the strength and that the drying period had only limited effect on the structural characteristics, except initial stiffness deterioration. Moreover, the results for specimens subjected to drying showed better agreement with the results of the observation record analysis of the reactor building than those not subjected to drying. Hence, the combination of drying shrinkage and seismic loads is considered to be responsible for the reduced initial stiffness of the Onagawa NPP buildings.

INTRODUCTION

The stiffness reduction of RC shear wall in-service period caused by a subtle mix of microearthquake and drying shrinkage characteristic of concrete affects the vibration characteristics in response analysis. However, it is considered that these characteristic does not affect the ultimate strength and deformability. The main objective of this study is to grasp the seismic performance of the walls, such as failure mode,

hysteresis characteristic and deformability to clarify stiffness reductions caused by the drying shrinkage characteristic of concrete and micro earthquakes in the vicinity of the first break point to the second one in the restoring force characteristic curve for response analysis.

Aizawa, Sakurai, and Sugawara (2017) conducted a high precision static loading test for RC shear walls from slightly deformed region (drift ratios $R = 1/10000$ rad.) to ultimate deformed region (1/100 rad.) to investigate stiffness reduction of RC Shear walls effect on damages from micro earthquakes. However, some specimens with some slightly notches arranged on the back of the web wall to simulate dry contraction of the initial cracks were not significant difference.

In this study, the static loading test of RC shear walls varied a curing method or drying period under the same conditions as the past were carried out to the effect of drying shrinkage on initial stiffness and the ultimate strength.

OVERVIEW OF EXPERIMENT

Outline of specimen

Figure 1 illustrates the front elevation of specimens and **Table 1** shows description of specimens. These details were determined by reference to Aizawa, Sakurai, and Sugawara (2017). Specimens were created by simulating RC shear wall of a nuclear power facility. Specimens consisted of a web wall having a thickness of 100 mm and flange walls having a thickness of 150 mm, width of 700 mm. As for the arrangement of rebars, both vertical and horizontal wall reinforcement bar ratio in web walls is about 1.4% considering the general situation of rebar arrangement in a nuclear power facility. In addition, in order to prevent bending yield of flange walls from preceding, the vertical reinforcement bar ratio of flange walls was 2.8%. Each Specimen were casted concrete at June 28, 2017.

The experimental variables investigated were the curing method and drying period. Specimen WM were shielded by formworks or aluminium tapes from after demolding to the installation for loading tests, i.e 3month, with the intention of occurrence prevention of cracks for dry shrinkage, while Specimens WD2 and WD3 were exposed to air only by exposing the web wall by curing the shield with aluminium tape at

Table 1: Section Properties of Specimen.

		CP	RCP	WM	WD2	WD1
Usage		Long-term Measurement		Loading Test		
Shape		wall plate		H Type Wall (with Stabs)		
Curing method		Exposed		Shielded	Exposed	Exposed
Tested		-----	-----	Oct. 5, 2017	Oct. 12, 2017	Mar. 7, 2018
Web Wall	Thickness	100 mm				
	Vert. & Hori. Rebar	None	Each face ($p_s = 1.4\%$ in both Vert. and Hori.)			
	Wall Length	1350 mm		1650 mm		
Flange Wall	B x D	-----		700 x 150 mm		
	Main Rebar	-----		16-D16 ($p_g = 2.8\%$)		
	Hoop	-----		2-D10@100 ($p_s = 0.95\%$)		

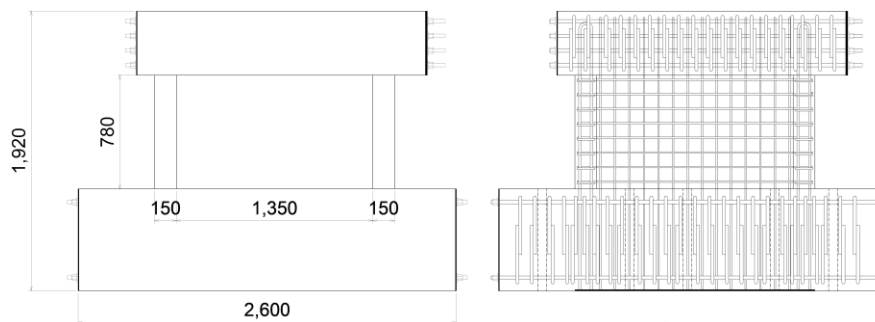


Figure 1. Configuration and bar layout of Specimens (unit: mm).

all sites of the specimen except the web wall after demolding. Then, Specimen WD2 exposed in 3-month and tested at October 12, 2017, while Specimen WD1 exposed in 8-month and tested at March 7, 2018.

The long-term measuring specimens CP and RCP were flat plate from which only the web wall portion is taken out to investigate the effect of flange-stab frames of Specimens for loading tests and wall bars on the drying shrinkage strain of the web wall during the exposure period. The experimental variable was the presence or absence of wall reinforcements. Specimen CP was made of unreinforced concrete except for the D6 rebar for strain measurement, while Specimen RCP has the same reinforcement layout as Specimen for loading tests.

Table 2 shows the material properties. As the coarse aggregate used, sandstone-based materials with a maximum particle diameter of 10 mm and a large drying shrinkage were used because the covering depth of the cross section of Specimens is small and it is necessary to promote the drying shrinkage action.

Long-term strain Measurement

The strain measurement of the reinforcing bar at the main site of the shear wall and the strain measurement of the concrete surface of the web wall were carried to grasp the influence of the drying shrinkage action of concrete on RC shear walls. The strain measurement of the rebar was carried out at a cycle of 4 times a day from after demolding by the strain gauge attached to the rebar. The surface strain was measured at gauge mark intervals of 100 mm on the surface of the web wall panel with contact gauges every other week. In addition, when gauge mark measurement of Specimen WM, the formwork was temporarily removed, and after measurement, water was sprayed by mist blowing, and the formwork was reinstalled.

Loading Program

Figure 2 shows the overview of the loading apparatus. This experiment was conducted in the Structure Test Laboratory of the Special Test Building, Akita Prefectural University. Specimen was fixed to a reaction

Table 2a: Material Properties of Specimens (Rebar).

Size (Steel Grade)	Location	Yield Point (N/mm ²)	Young's Modulus (kN/mm ²)	Tensile Strength (N/mm ²)
D10 (SD295A)	Wall Rebar	367	199	506
D16 (SD295A)	Column Main Rebar	367	197	525

Table 2b: Material Properties of Specimens (Concrete).

	4 Weeks	8 Weeks	12Weeks	WM Test	WD2 Test	WD1 Test
Age (day)	28	54	82	101*	108*	253*
Comp. Strength (N/mm ²)	30.6	31.5	33.9	35.5	34.3	38.7
Young's Modulus (N/mm ²)	----	----	----	25.8	27.0	28.4
Poisson's Ratio	----	----	----	0.181	0.177	0.193

* Conducted at the day after loading starts

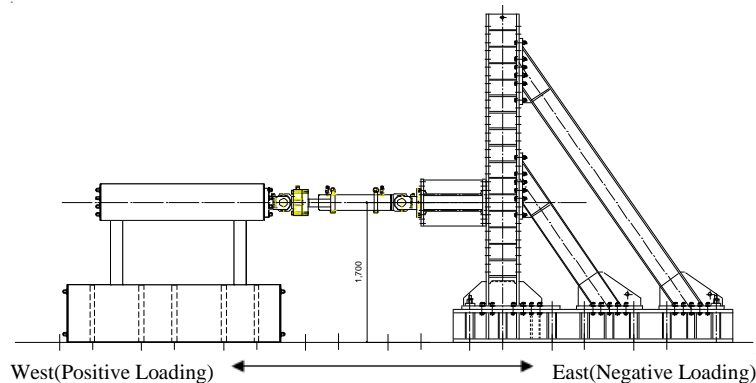


Figure 2. Loading Apparatus.

floor by PC steel bars and horizontally subjected to Cyclic loadings by two jacks (pushing: 2000 kN and pulling: 1000 kN) mounted on a reaction frame.

Table 3 shows the loading program. This experiment adopted the displacement control method as loading systems during testing. In this study, the loading cycle of $R = 1/10000$ rad. to $1/1250$ rad are defined as slightly deformed region. The experiment was firstly carried out under 2-cycle loadings at the loading cycle of $R = 1/10000$ rad. and $1/5000$ rad.. Then, the loading program was basically planned as 5-cycle loadings at each drift angle for each principal displacement. And at the latter part after the loading cycle of $R = 1/1000$ rad., the loading program was planned as 2-cycle loadings. In addition, for the purpose of studying stiffness reduction behavior at medium and small amplitudes, repeated loading that forms an inner loop was carried out for a total of 4-cycles. Furthermore, although repeated 2-cycle loading was planned after the loading cycle of $R = 1/1000$ rad..

LONG-TERM MESURING RESULT

Cracks by visual measurement

Figure 3 shows the crack status of Specimen CP about 3 months after the placement and Specimens WM, WD1 and WD2 just before loading tests. In the figure, the position of gauge marks for contact gauge measurement are also shown.

In Specimen CP, it was confirmed no remarkable cracks, while in exposed Specimens, it was visually confirmed horizontal cracks from the middle to the lower part of the web wall at the end of July 2017, which is four weeks after the placement.

Table 3. Loading Program

Loading Step	Drift Angle (rad.)	Disp. (mm)	Num. of Loading Cyc.	Loading Step	Drift Angle (rad.)	Disp. (mm)	Num. of Loading Cyc.	
1	slightly deformed region	1/10000	0.100	2	9	1/1000	1.000	2
2		1/5000	0.200	2	10	1/500	2.000	2
3		1/3333	0.300	5	11	1/333	3.000	1
4		1/5000'	0.200	2	12	1/250	4.000	1
5		1/3333'	0.300	2	13	1/200	5.000	1
6		1/2500	0.400	5	14	1/133	7.500	1
7		1/1667	0.600	5	15	1/100	10.00	1
8		1/1250	0.800	5				

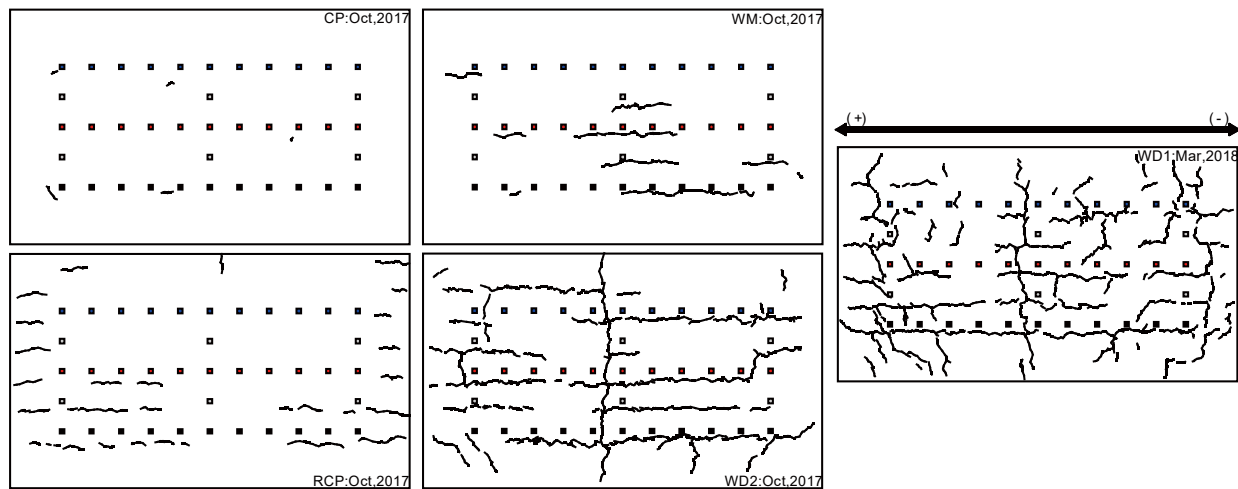


Figure 3. Crack Status in Exposed Term.

In the strain measurement results between gauge marks, it was showed that the tendency of strain increases in compressive due to dry shrinkage is larger than that of other Specimens because Specimen CP has almost no effect of restraint due to the non-reinforcement. Then, the number of cracks increased with the passage of the aging days in the test specimens. In Specimen WD2, vertical cracks were also observed.

Compared with Specimen CP, Specimens RCP and WD2 occurred horizontal cracks further and tend to occur cracks along horizontal bars. Therefore, it seems that internal reinforcements cause cracks due to local tension by constraining the drying shrinkage of concrete. From the comparison of the test body RCP with WD2 and WD1, it considered that the restraining action of stubs and flange walls around the web wall causes an increase of cracks and oblique cracks in the vertical direction and the lower corner of the central part. On the other hand, compared with Specimens WD1 and WD2, the results showed almost the same tendency of cracking regardless of the difference in curing period.

In addition, although the number was small also about Specimen WM, some cracks of the horizontal direction were observed. This is because the self-shrinkage action of the concrete in the specimen WM and the exposure condition for 1 week after the demolding to the loading test provoked the slight drying shrinkage.

Time histories of strain

Figure 4 shows the results of averaging surface strain of concrete for each row or column measured with a contact gauge as a time history. In the figure, the strain measurement value on July 6, 2017, when measurement starts, is calculated as 0. **Figure 5** also shows the transition of strain gauges at vertical and horizontal rebars in the center of the web wall. In both figures, the positive value is in tension and the negative value is in compression.

As shown in **Figure 4**, the strain tends to gradually increase with aging for any part at wall panel. In addition, the increase in shrinkage strain tended to be larger in Specimens CP and RCP with the wall plate only than Specimens WM, WD2 and WD1 with stubs and flange walls. Especially, the increase in Specimen CP was the largest. The vertical and horizontal strain in Specimen CP in September 17, 2017 which curing period was passed 3-month was about -600μ . While in Specimen RCP with rebars, Specimens WM, WD2 and WD1 with stubs and flange walls were about -200μ at the maximum. During the 3rd to 8th months of

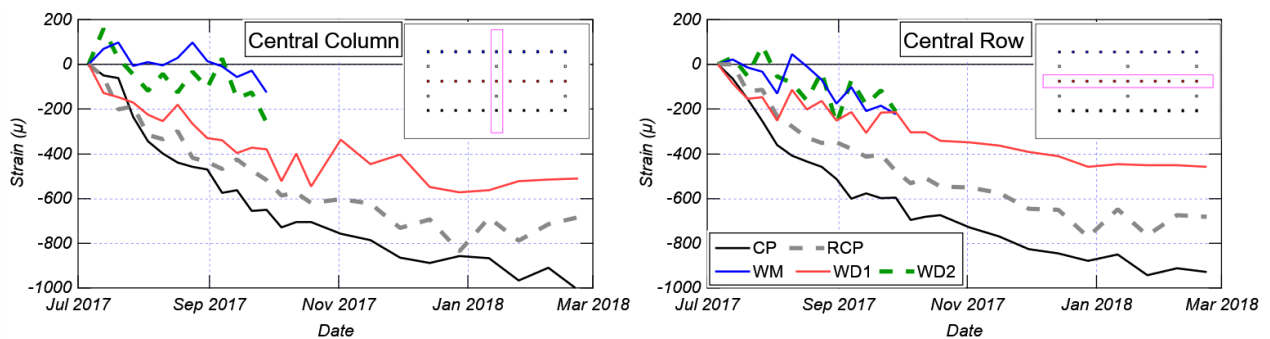


Figure 4. Strain between Gauge Marks on Concrete Surface.

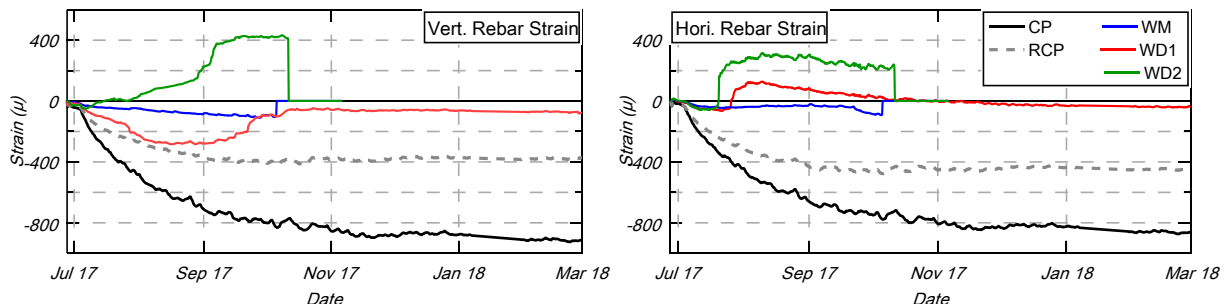


Figure 5. Strain at Rebars of the Center of Wall Panels.

exposure, although the tendency for the increase in compressive strain in Specimens CP and RP eases, the compressive strain continues to gradually increase. On the other hand, the strain transition in specimen WM with shield from after the placement to the 3 months had a tendency similar to Specimens WD2 and WD1.

As shown in **Figure 5**, the strain of the Specimen CP in of September 19, 2017 was the largest at about -800μ , and then Specimens RCP, WM tend to decrease similarly as in Figure 5. However, in Specimens WD1 and WD2, vertical and horizontal rebar strains tended to shift from in compression to in tension with the passage of the aging days. In Specimens RCP, WD1 and WD2, shrinkage strain near the strain measurement point is smaller than that of Specimen CP due to the restraint effect by the internal reinforcement rather than the drying shrinkage behavior of concrete. Furthermore, in the case of Specimens WD2 and WD1 where the rebar ends of the web wall is fixed to the other members, it is considered the strain is shifted to the tension side by the restraint action of peripheral members.

In Specimen WD1 at an exposure period of about 8 months, the increasing tendency of compressive strain becomes moderate after 3 months from the start of curing and was almost equivalent to Specimens CP and RCP. Compared with Specimen WD2, it is considered that the difference in the tendency of compressive strain with the difference in curing period is small.

From the above, with the lapse of the curing days, the strain of concrete due to drying shrinkage of Specimen CP without peripheral restraint became the largest. On the other hand, in Specimen RCP with rebar restraint and Specimens WD2 and WD1 with restraint by peripheral members, tensile forces were generated locally due to each restraint action, and crack was generated. Furthermore, the strain tended to decrease.

STATIC LOADING TEST RESULT

Damage process and hysteresis loop

The shear force versus displacement relationships and envelopes of Specimens are shown in **Figure 6**, and the final failure using Specimen WM as an example are shown in **Photo 1**.

In the loading cycle of $R = 1/5000$ rad., the occurrence of the first crack due to loading on the web wall was confirmed for each Specimen. However, this crack developed newly from the edge of the crack

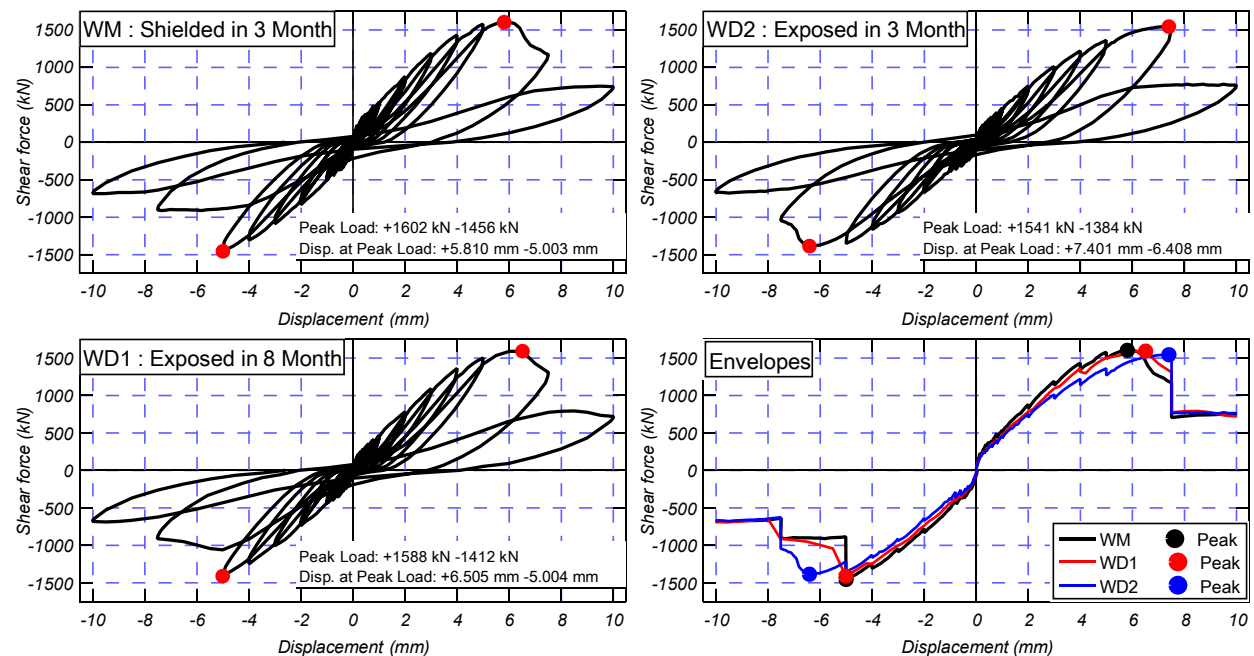


Figure 6. Shear Force Versus Displacement Relationships and Envelopes

by drying shrinkage which occurred in the web wall during the curing period, unlike the crack by a general loading experiment of shear walls. Then, the increase of new shear crack in the oblique direction was confirmed with the increase of loading amplitude, and the damage progress was almost similar to the Specimen WCD in 2015 (Aizawa, Sakurai, and Sugawara (2017)). As shown in **Figure 6**, the maximum strength of 1604 kN at 5.8 mm was recorded for Specimen WM, 1541 kN at 7.4 mm for Specimen WD2, and 1588 kN at 6.5 mm for Specimen WD1. At the same time, as shown in **Photo 1**, shear slip occurred along the site of drying shrinkage crack in all Specimens, and a clear decrease in shear force was observed.

From **Figure 6**, the shear force at the displacement peak of each loading cycle showed a difference in each Specimen for each cycle, and Specimen WM was the highest and Specimen WD1 and Specimen WD2 became smaller in this order. As for the deformation at the maximum strength, Specimen WD1 was 0.7 mm larger than Specimen WM and Specimen WD2 was 1.6 mm larger than Specimen WM.

As a result, the stiffness of Specimens WD1 and WD2 tended to be lower than that of Specimen WM, because of drying shrinkage cracking, while the maximum strength of Specimens WD1 and WD2 was almost the same as that of Specimen WM, although there was a maximum difference of 4.0%. A slight difference in stiffness was observed between Specimens WD1 and WD2, but the difference in the number of days of exposure had a smaller effect on stiffness because Specimen WD1 had higher stiffness than Specimen WD2.

Stiffness reduction and cumulative dissipated hysteresis energy

Figure 7 shows the transition of rigidity and cumulative dissipated hysteresis energy of Specimens in each loading cycle, and **Figure 8** shows the transition as the ratio of Specimens WD1 and WD2 to Specimen WM. For the stiffness used in both figures, the so-called “peak to peak stiffness” was calculated as the slope when the peak points on the positive and negative loading sides of the same loading cycle were connected by a straight line in the shear force versus displacement relationship. The cumulative dissipated hysteresis energy is the sum of the history area of each loading cycle in the shear force versus displacement relationship from the start of loading.

The stiffness in the loading cycle of $R = 1/10000$ rad. was 1624 kN/mm for Specimen WM, 1284 kN/mm for Specimen WD2 and 1397 kN/mm for Specimen WD1. Then, the stiffness decreased with the increase of loading amplitude, and it observed almost equivalent to 71.4 kN/mm in Specimen WM, 71.5 kN/mm in Specimen WD2, and 70.0 kN/mm in Specimen WD1 in the loading cycle of $R = 1/100$ rad. which is the final loading. In each Specimen, there was a remarkable stiffness reduction in the loading cycle in which the displacement renewal occurred, and in the loading cycle in which the identical displacement is repeated, the stiffness lowered slightly.



Photo 1. Final Failure (Specimen WM).

The cumulative dissipated hysteresis energy in the loading cycle of $R = 1/10000$ rad. was 15.9 kNmm for Specimen WM, 10.6 kNmm for Specimen WD2, and 13.0 kN mm for Specimen WD1. Then, the energy increased with the increase of loading amplitude, and it observed almost equivalent to 24774 kNmm in Specimen WM, 24220 kNmm in Specimen WD2, and 23942 kNmm in Specimen WD1 in the loading cycle of $R = 1/100$ rad. which is the final loading.

As for the ratio of the energy of Specimens WD1 and WD2 to WM, the ratio in the loading cycle of $R = 1/10000$ rad. immediately after the start of loading was about 0.6, showing a large difference for each Specimen. However, the difference gradually observed smaller as the loading amplitude increased, and in the loading cycle of $R = 1/100$ rad. cycle, which is the final loading, the ratio was nearby 1.0, which was almost the same. It is inferred that the energy consumption of Specimens WD1 and WD2 was close to the equivalent value in the final loading cycle, because the deformation of Specimens WD1 and WD2 at the maximum strength observed larger than Specimen WM by the effect of drying shrinkage crack.

From the above results, the stiffness of Specimen WD2 exposed for 3 months was about 20% of that of the shield-cured Specimen WM, while those in specimen WD1 exposed for 8 months was about 10%. While these results were due to the effect of crack generated in the web wall by drying shrinkage, the maximum strength and cumulative dissipated hysteresis energy are equivalent for each Specimen.

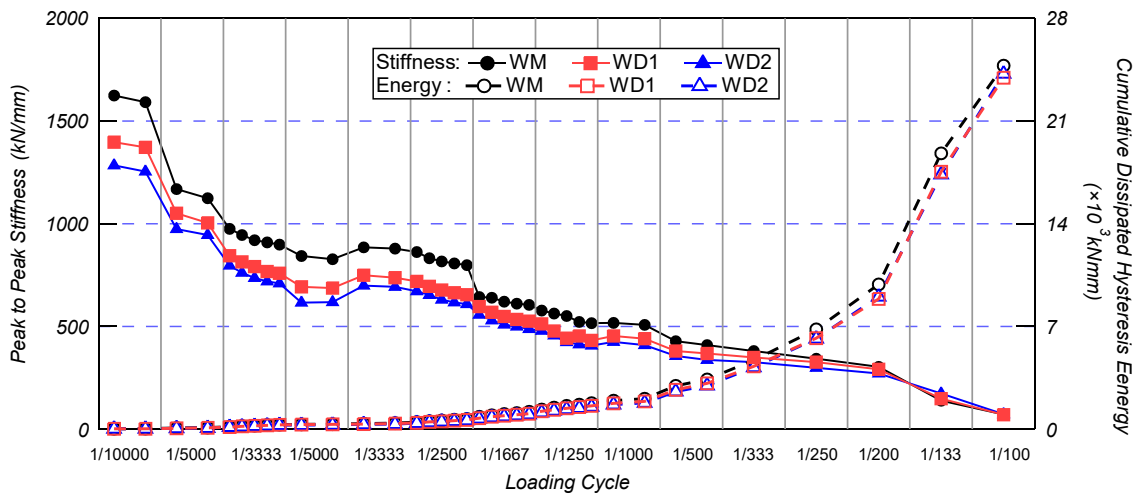


Figure 7. Transition of Stiffness and Cumulative Dissipated Hysteresis Energy

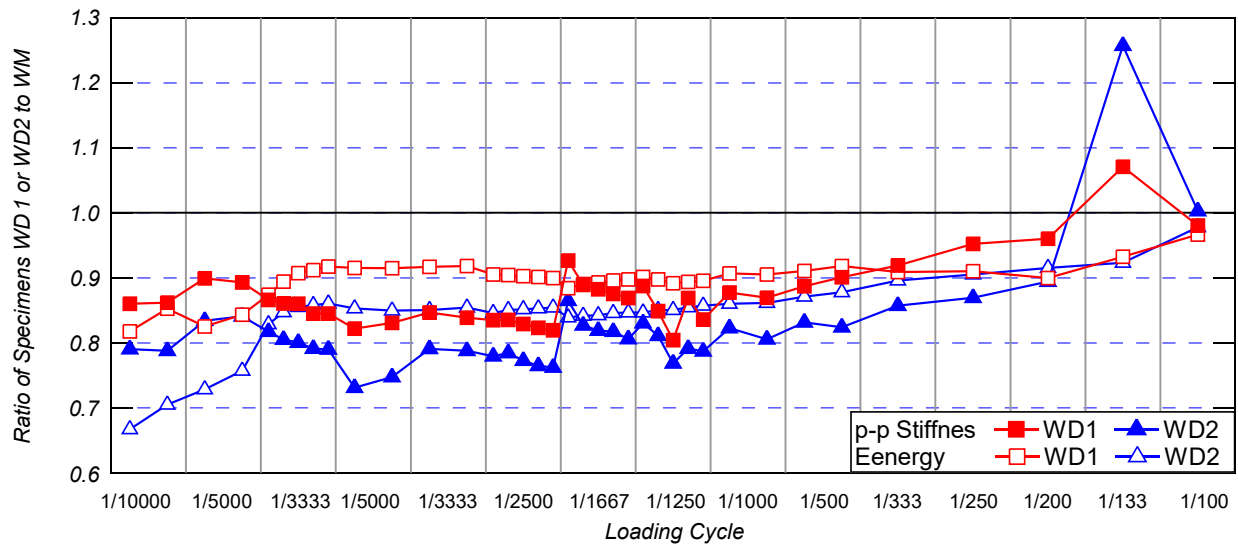


Figure 8. Transition of Raito of Stiffness and Cumulative Dissipated Hysteresis Energy

COMPARISON OF THE RESULTS OF TESTS WITH THOSE OF EARTHQUAKE OBSERVATION RECORD ANALYSIS OF THE ACTUAL REACTOR UNIT

Figure 9 compares the results of Static Loading Test [2] with those of earthquake observation record analysis of the actual reactor unit. **Figure 10** shows downward trend in natural frequency of horizontal direction at Onagawa NPP Unit No. 2 reactor building.

The former and latter results are largely in agreement with each other regarding the amounts of stiffness reduction in the Onagawa NPP Unit No. 2 reactor building due to the major earthquakes (2005 Miyagi Earthquake and 311 Earthquake) (the amounts of decrease in stiffness from the as-built value).

The result of this comparison shows that the initial stiffness decreased more significantly than expected when designed because of the combined effect of the drying shrinkage of concrete and the impacts of factors, such as the 311 Earthquake.

* Specimen not affected by drying shrinkage

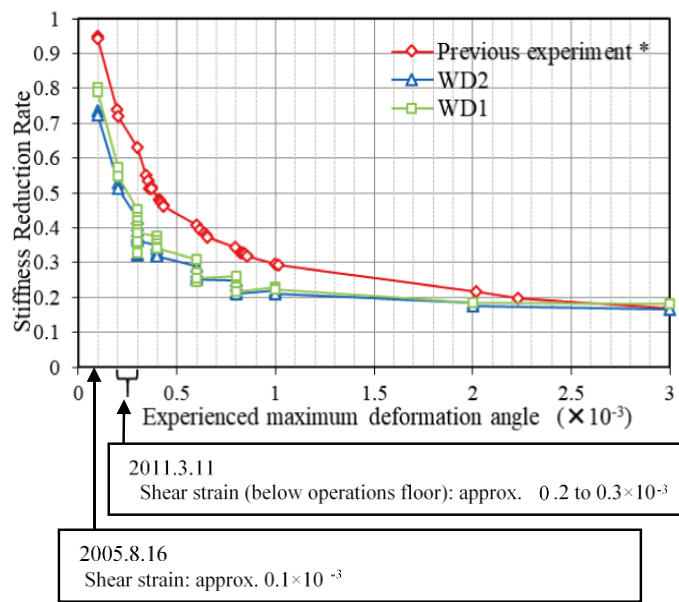


Figure 9. Comparison of stiffness reduction rates.

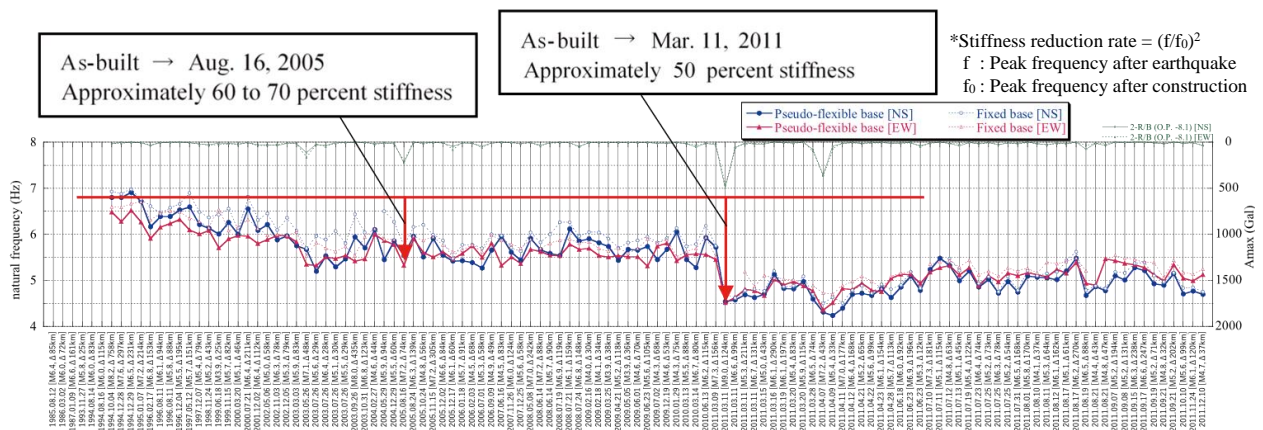


Figure 10 Downward trend in natural frequency of horizontal direction.
 (Onagawa NPP Unit No. 2 reactor building)

CONCLUSION

The static loading test of RC shear walls varied a curing method or drying period were carried out to the effect of drying shrinkage on initial stiffness and the ultimate strength. Furthermore, it discussed the comparison of the test results with those of earthquake observation record analysis of the actual reactor unit. The following conclusions are obtained.

From the result of long-term strain measurement, almost no crack was observed in the plain Specimen CP. On the other hand, cracks due to drying shrinkage of concrete were observed in other Specimens depending on the degree of restraint action by rebars and peripheral members.

With the progress of curing days, shrinkage strain of Specimen CP without restraint by peripheral members were the largest by drying shrinkage action. On the other hand, in Specimen RCP with reinforcement restraint and Specimens WD1 and WD2 with restraint by peripheral members, the strain by the measurement between gauge marks were small, because the crack was generated by the restraint action.

From the result of static loading tests, it was found that the Specimens exposed for a long term showed about 20% decrease in stiffness and increase in deformation at maximum strength in comparison with the Specimen WM of shield curing by the action of crack generated in the web wall by drying shrinkage. On the other hand, the maximum strength and energy consumption were almost the same as those of each Specimen.

The result of the comparison the test results with those of the actual reactor unit shows that the initial stiffness decreased more significantly than expected when designed because of the combined effect of the drying shrinkage of concrete and the impacts of factors, such as the 311 Earthquake.

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