Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division IX (include assigned division number from I to X)

APPLICABILITY EVALUATION OF STEEL PLATE REINFORCED CONCRETE STRUCTURE TO PRIMARY CONTAINMENT VESSEL OF BWRs
(11) OPENING PART TEST

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ABSTRACT

Heating tests and in-plane tensile tests were conducted to investigate the structural properties of steel plate concrete walls with openings which simulated a steel plate reinforced concrete structured containment vessel (hereafter abbreviated as an “SCCV”) under high temperature and internal pressure in the event of a severe accident. The test specimens were 1/12-scale models of approx. 20m long x 20m wide x 2m thick wall with openings of the SCCV. The wall thickness of the specimen was 167mm, and the steel plate thicknesses of both sides of the wall were 1.7mm. Test parameters were the size and the number of openings. No-opening specimen has no openings. Large-opening specimen has one large circular opening. Group-opening specimen has six small circular openings. To reinforce the steel plate of the circular opening, the steel plate around the opening was thickened to 3.4mm i.e. twice the thickness of the steel plate of a general part. To reproduce the temperature distribution in the event of a severe accident (hereafter abbreviated as an “SA”), one side of the specimen was heated to a fixed temperature of 300°C, while the other side was cooled to a fixed temperature of 74°C. Afterwards, a tensile force equivalent to the internal pressure in the event of an SA was applied to the four sides of the specimen. Test results showed that the load versus mean strain relationship of the large-opening specimen and group-opening specimen have almost the same properties as no-opening test specimen. Besides, no damage was observed at the opening edge. Thus, the tests confirmed that the opening reinforcement method was appropriate. Moreover, simulation analyses of individual tests were conducted using a finite element method, which confirmed that the analytical results closely corresponded to the results of experiments.

INTRODUCTION

Reinforced opening parts of an SCCV are subjected to in-plane tensile force due to internal pressure caused by an SA. This paper reports the results of in-plane tensile tests and simulation analyses conducted to determine the load-deformation relationship and stress states of reinforced opening parts of the SCCV in the event of an SA. The test specimens were 1/12-scale models of approx. 20m long x 20m wide x 2m thick wall with openings of the SCCV. In-plane tensile tests were conducted after the heated specimens had been cooled naturally.

EXPERIMENTAL DETAILS

Target Areas to be Tested and Opening Reinforcement Method

The target areas of tests were the large opening of an L/D access tunnel, which is the largest opening of an SCCV, and an MS/FDW group opening, which comprises relatively large many openings, as indicated in Fig. 1. In the event of an SA, the containment vessel is assumed to be subject to 480kPa internal pressure, 300°C internal temperature, and 74°C external temperature. As shown in Fig. 2, "Standards on Design and Construction for Nuclear Power Plants[1)]" was applied to design the opening reinforcements. These standards stipulate the reinforcement as follows: when the opening diameter is expressed as D, the steel plate thickness within a 0.5D range of the opening periphery should be increased to twice of general parts. Furthermore, the steel plate thickness among group openings was designed as a continuum of the thickened sections.

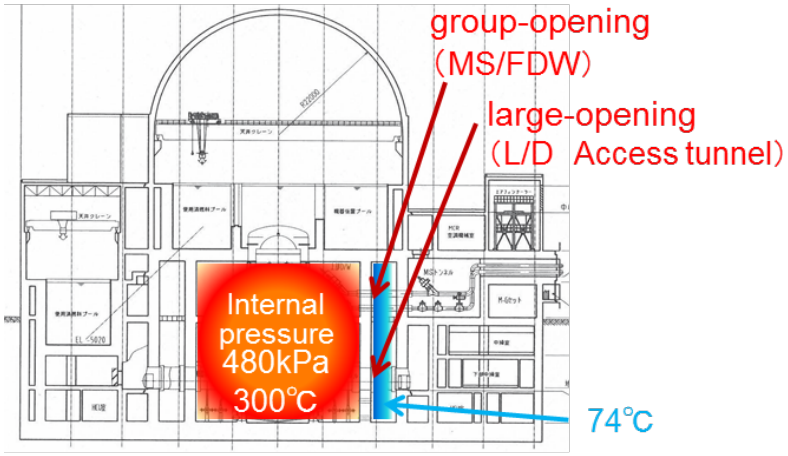


Figure 1. Opening position and accident condition

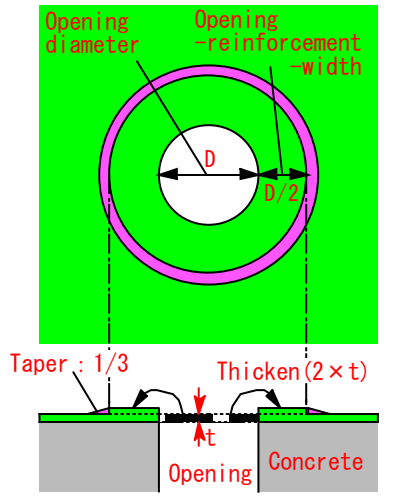


Figure 2. Opening reinforcement method

Test Parameters and Test Specimens

The test parameters were with or without openings, and opening shape. Three test specimens were tested: a no-opening one, a large-opening one, and a group-opening one. As shown in Fig. 3, the test specimens were 1/12 scale of the assumed actual SCCV and the materials were the same. Fig. 4 and Fig. 5 show the shapes and dimensions of the large-opening test specimen and the group-opening test specimen. The shape of the no-opening test specimen was the same as that of the opening test specimens. The test area of the specimens was 1.8m square and they were 167mm thick. Each of the four sides had a 175-mm-wide loading jig fixing part. The overall test specimens were 2.15m square. In addition, the loading jig fixing part had slits at certain intervals to block stress transition so that the loading jig fixing part would have no impact on the yield strength of the test area in the orthogonal loading direction. The main steel plate of the test area was set to 1.7mm thick, which is approx. 1/12 of 20mm: the thickness of the general part of the assumed actual SCCV. The steel plate of the reinforced opening part was 3.4mm thick, which is twice of the thickness of the general part of the steel plate. The material used for both steel plates was SPV490. Headed studs (axis diameter: 3.45mm, under head length: 28mm) were placed on the internal plane of the

steel plate at 34mm horizontal and vertical intervals. The target compressive strength of the concrete was within the range of 30 to 40N/mm^2, which is the same as that of the assumed actual SCCV. Crushed sandstone up to 10mm particle size was used for the aggregate.

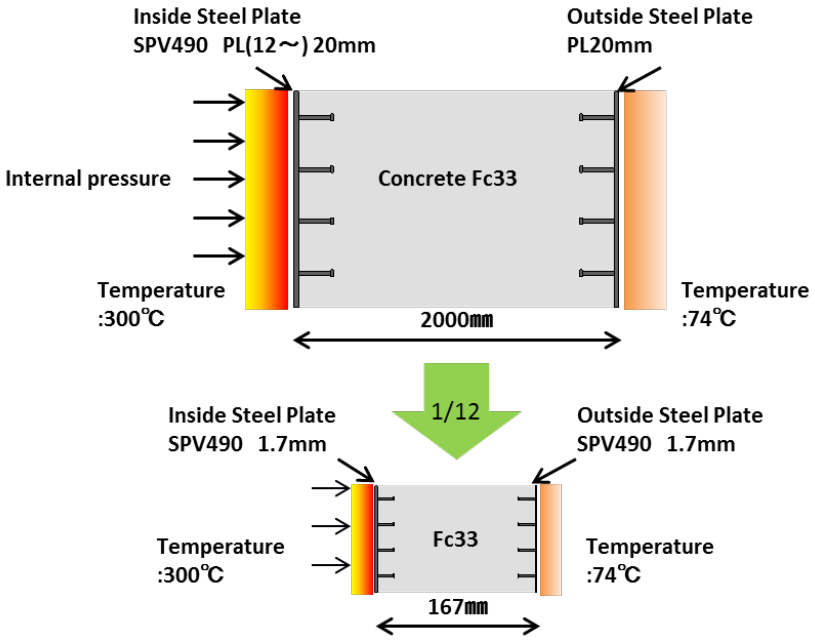


Figure 3. Reduced scale of the test specimen

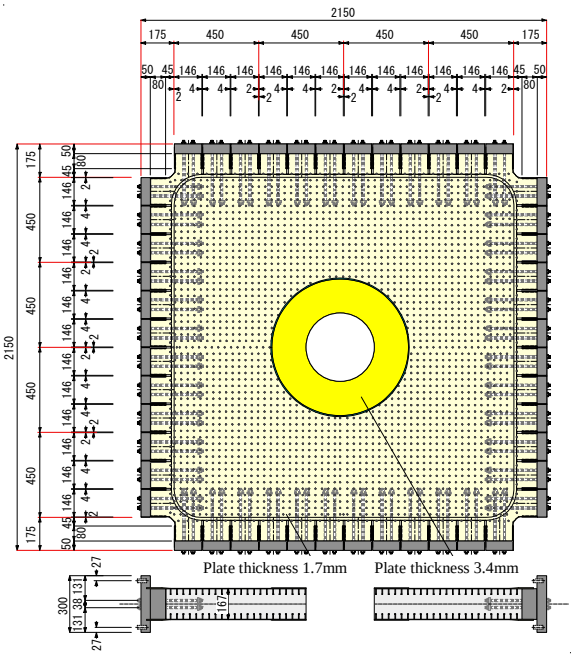


Figure 4. Shape of the test specimen (Large-opening)

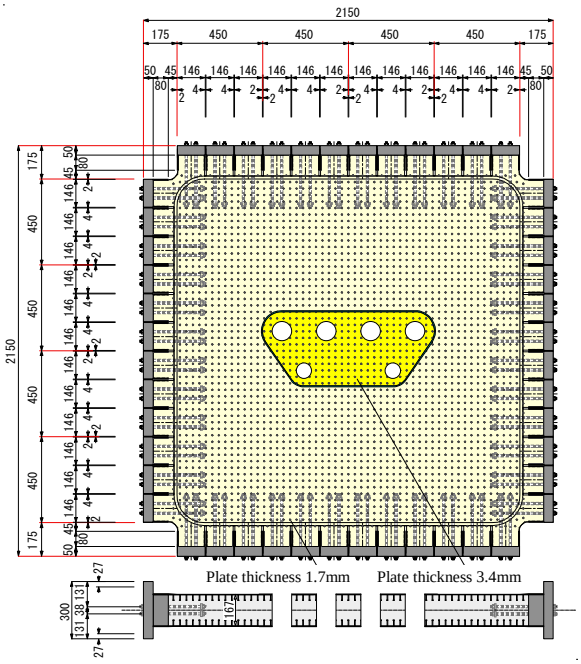


Figure 5. Shape of the test specimen (Group-opening)

Test Method

In-plane tensile tests were conducted after the heated specimens had been cooled naturally. As shown in Fig. 6, in the heating tests, the test specimens were installed horizontally on the frame. The temperature distribution in the event of an SA was reproduced in the state where the upper side of the test specimen was heated to a fixed temperature of 300°C using a heater while the lower side was kept at a fixed temperature of 74°C using a heat insulating and cooling device. The heating time was set to five hours. The time allowed us to check the long-term heating impact affecting the concrete's mechanical characteristics (compressive strength and modulus of elasticity). Afterwards, the test specimens were left to cool naturally. After the cooling finished, the loading test was conducted in a state in which the test specimens were installed horizontally on a loading device as shown in Fig. 7. At that time, the test specimens were put on four support stands made of Teflon so that they had no out-of-plane bending due to their self weight. For loading, a two-axis tensile force, generated in the internal plane of the SCCV due to internal pressure (480kPa) in the event of an SA, was applied to the four sides of the test specimens. Two-axis tensile forces were applied in accordance with the procedure shown in Fig. 8. The ratio of the tensile force in the X direction (circumferential to the actual SCCV) and in the Y direction (perpendicular to the actual SCCV) was kept at 2:1, which is the same as the ratio of tensile forces when internal pressure was applied. The two-axis tensile forces were increased until the yield of the steel plates travelled through the test specimens.

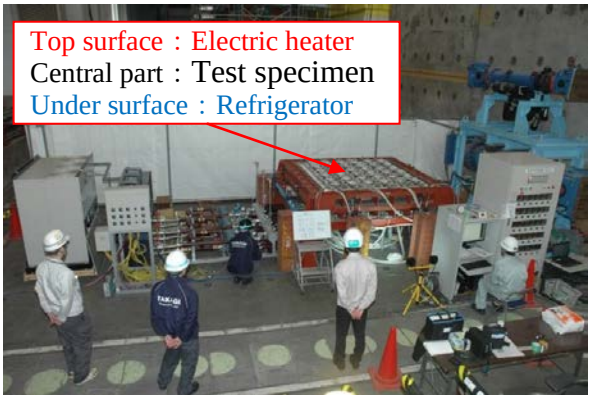


Figure 6. Heating and cooling device

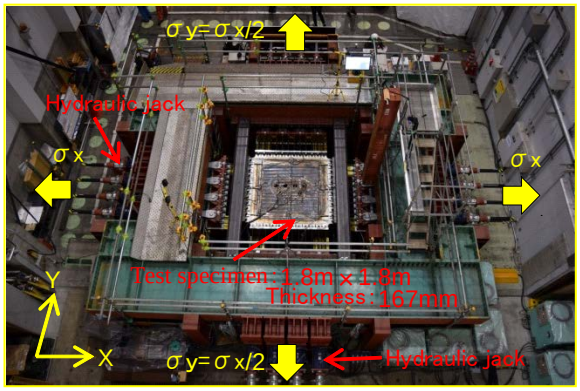


Figure 7. Loading device

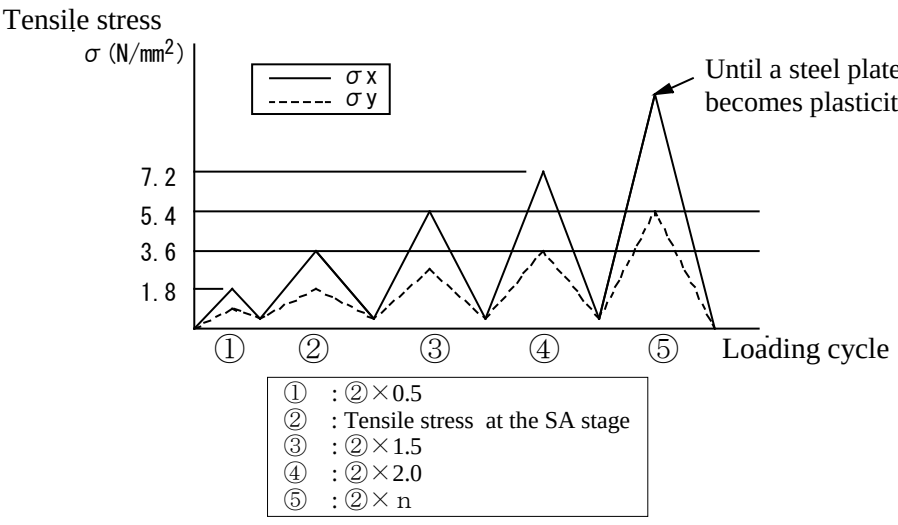
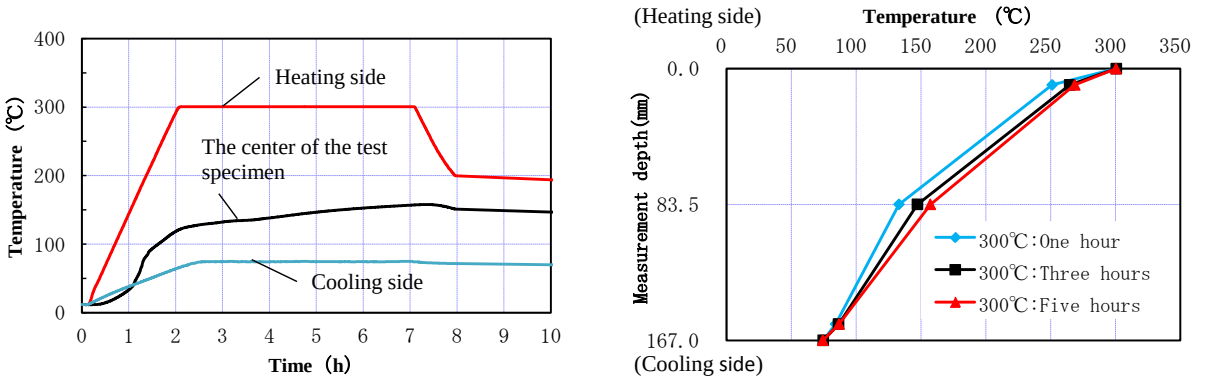


Figure 8. Loading procedure

Test Results

Results of Heating Tests

Fig. 9 shows changes in temperatures of the large-opening test specimen and the temperature distribution in the thickness direction of the specimen during heating. The temperatures of the test specimen indicate the mean values measured by thermocouples placed evenly in the direction of the test specimen thickness on the surface and in the center of the specimen. The temperature of the test specimen was controlled so that the temperature of the heated side would become 300°C after approx. two hours from the start of heating, while the temperature of the insulated and cooled side would become 74°C. Afterwards, the temperatures of the individual surfaces were kept at those temperatures for five hours. Heating was stopped when it was confirmed that the internal temperatures were evenly distributed, and then the test specimen was left to cool naturally. Heating of the other test specimens, like the large-opening test specimen, was performed as planned in the predetermined thermal history.



Change of the temperature Temperature distribution of the thickness direction

Figure 9. Temperature measurement result of the test specimen (Large-opening)

Results of In-Plane Tensile Tests

In-plane tensile tests were conducted after the heated specimens had been cooled naturally. Fig. 10 shows the relationship between the mean tensile stress and the mean strain in the X-direction (circumferential direction of the actual SCCV) of the individual test specimens.

The mean stress in the X direction was evaluated by dividing the tensile load in the X direction by the cross-sectional area of the specimen. In addition, the mean strain in the X direction was evaluated as the overall mean strain of each section calculated on the basis of the individual relative displacements at the displacement measurement positions on the front and rear sides of the test specimen shown in Fig. 11. The relation between the mean tensile stress and the mean strain in the X direction of the large-opening and group-opening test specimens was almost the same as the relation for the no-opening test specimen. In addition, the ratio of stress in the steel plate of the individual test specimens at the tensile yield point to the assumed stress in the event of an SA ($3.6N/mm^2$) are approx. 4.0 for the no-opening test specimen and approx. 4.2 times for the opening test specimens.

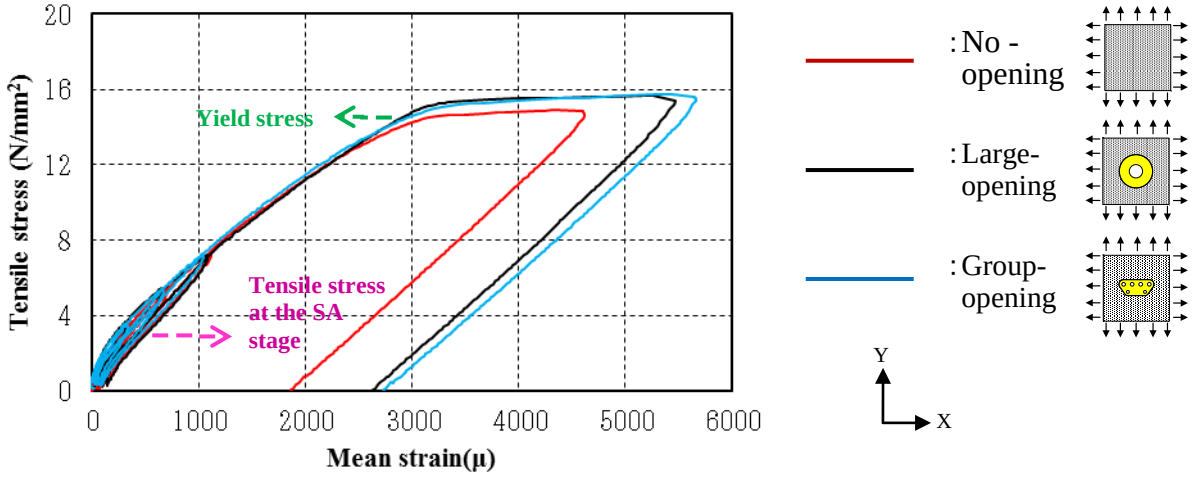


Figure10. Tensile stress - mean strain in X direction

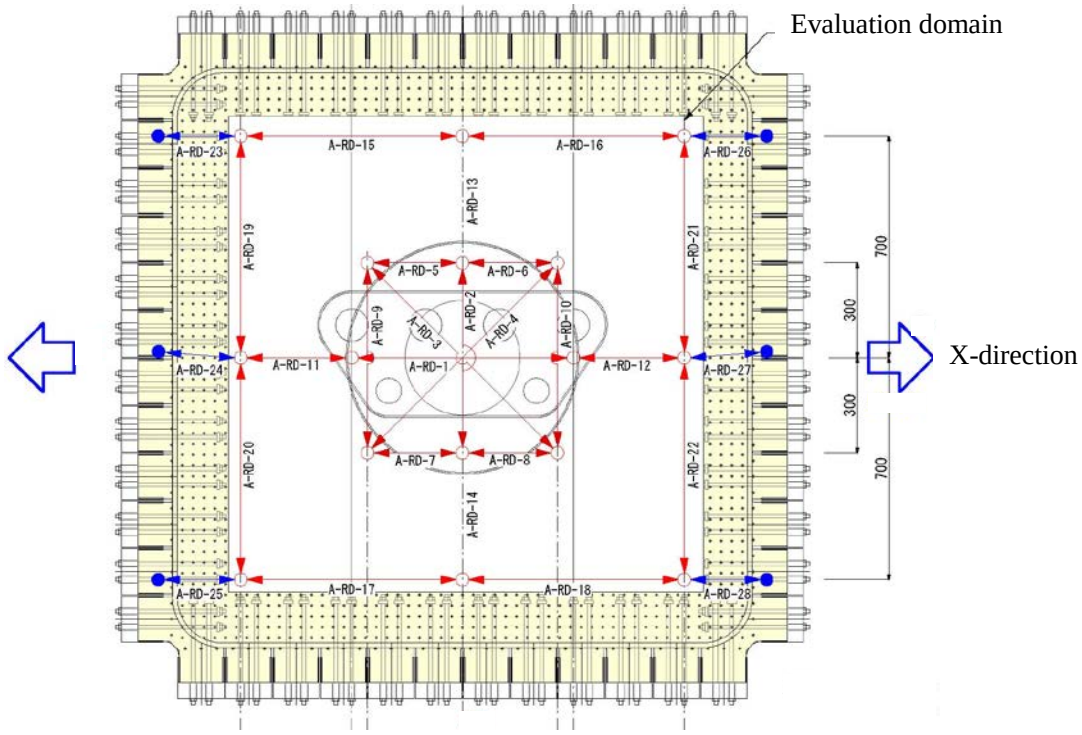
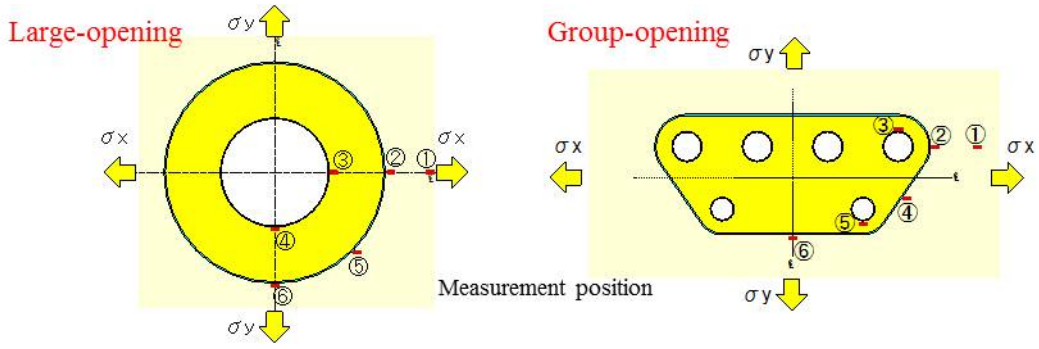


Figure11. Displacement measurement position

Fig. 12 shows the ratio between the measure strains of the opening periphery when assumed tensile force in the event of an SA was applied and the yield strain of the steel plate. The tensile strain in the event of an SA was largest at the opening verge (positions ④ of the large opening and ⑤ of the group opening) of the individual specimens in the X direction. However, these values were more than 4 times of the yield strain (2834μ) in the steel plate material tests. Moreover, the reinforced opening verge did not rupture after the general part of the steel plate yielded. These results confirmed that the adopted opening reinforcement method under in-plane tensile loading was appropriate.



Measurement position No.	Measurement strain (μ)	Yield strain /Measurement strain (ratio)
①	375	7.6
②	270	10.5
③	-47	—
④	632	4.5
⑤	328	8.7
⑥	240	11.9

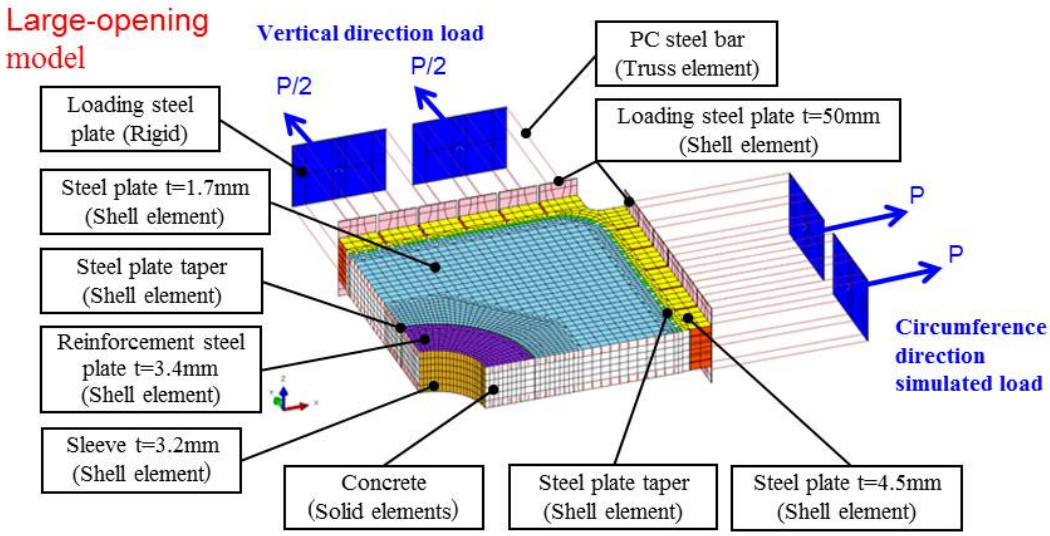
Measurement position No.	Measurement strain (μ)	Yield strain /Measurement strain (ratio)
①	357	7.9
②	323	8.8
③	472	6.0
④	534	5.3
⑤	647	4.4
⑥	299	9.5

Figure 12. Strain around the opening at the SA stage

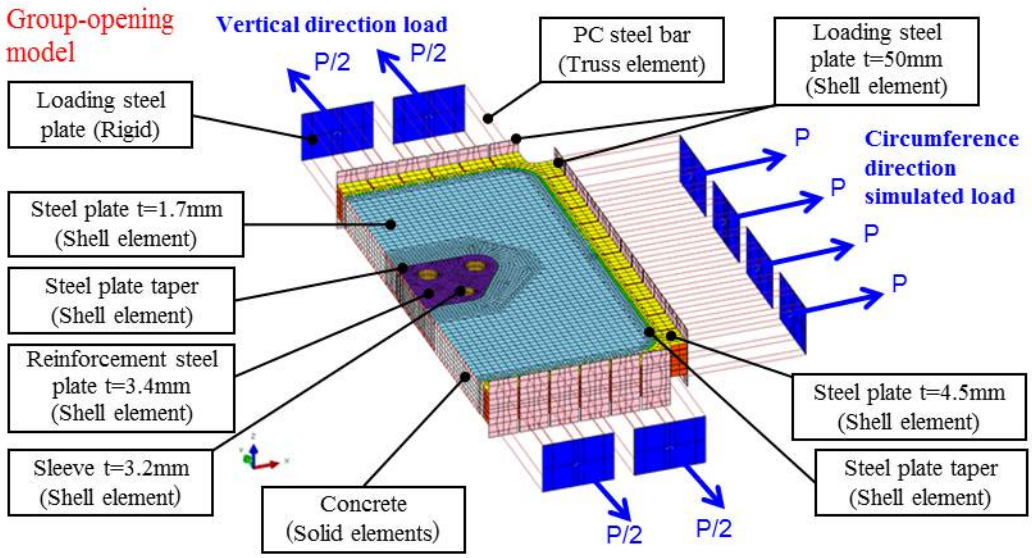
Test Simulation Analyses

Analysis Method

Simulation analyses of the in-plane tensile tests of the no-opening test specimen, the large-opening test specimen, and the group-opening test specimen were conducted using a finite element model of static elasto-plasticity. Fig. 13 shows analytical models of the large-opening and group-opening test specimens. For modeling, the no-opening test specimen and the large-opening test specimen adopted a 1/4 symmetrical model and the group-opening test specimen adopted a 1/2 symmetrical model, after considering the shape of the test specimens and symmetry of loading. In the test, the specimens were heated and cooled, before applying tensile force. In the analysis, the experienced maximum temperatures were sought by 3D non-stationary heat conduction analysis and the thermal degradation corresponding to the experienced temperature of concrete was considered for modeling. At that time, the thermal degradation by heating was evaluated by using reduction coefficients on compressive strength and coefficient on the modulus of elasticity which were calculated in accordance with "Eurocode-4". The same reduction coefficient was also applied to tensile strength. However, the stress analyses did not consider thermal deformation, thermal stress, or residual strain and stress after cooling.



Large-opening model



Group-opening model

Figure 13. Analysis models

Analytical Results

Fig. 14 through Fig. 16 shows the tensile-stress versus mean-strain relationship in the X direction, in comparison with the test results. The analytical results reproduced the relationship between the stress in the steel plate and the mean strain almost exactly from lowered initial stiffness to tensile yield strain. In addition, Table 1 lists the strain distribution of the opening periphery in the event of an SA and in the event of a three-times SA. The analytical results reproduced the test results almost exactly for the opening verge strain.

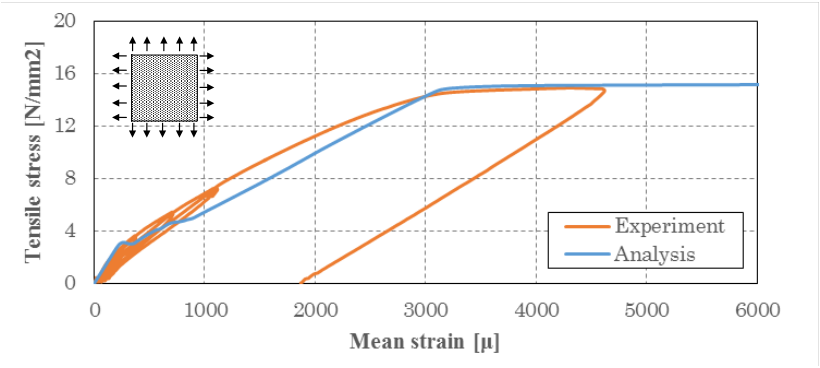


Figure 14. Tensile stress - mean strain relations of the X direction（No-opening）

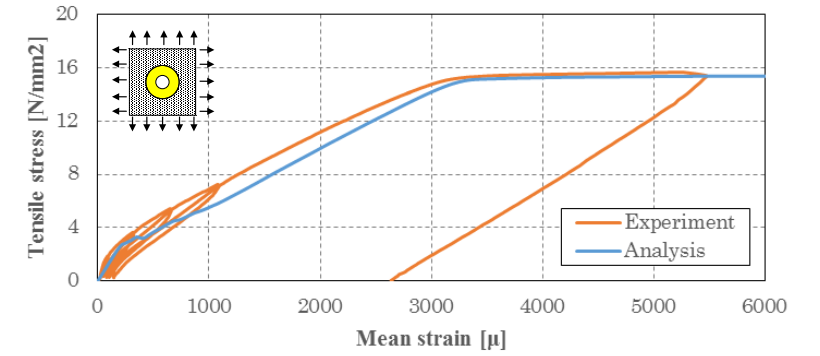


Figure 15. Tensile stress - mean strain relations of the X direction（Large-opening）

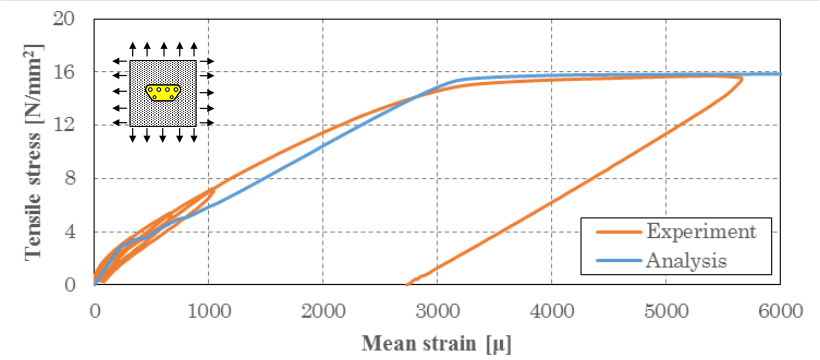


Figure 16. Tensile stress - mean strain relations of the X direction（Group-opening）

Table 1. Strain around the opening

	Large-opening				Group-opening			
	Experiment		Analysis		Experiment		Analysis	
Position No.	SA stage [μ]	3×SA stage [μ]	SA stage [μ]	3×SA stage [μ]	SA stage [μ]	3×SA stage [μ]	SA stage [μ]	3×SA stage [μ]
①	375	1500	561	2054	357	1590	685	2177
②	270	1080	304	1753	323	1782	416	1877
③	-47	-116	-26	-132	472	2336	795	2482
④	632	2486	1073	3827	534	2275	582	2175
⑤	328	1627	749	2804	647	3905	904	2472
⑥	240	1229	605	1775	299	1238	339	1415

※The measurement position refers to Figure 12

CONCLUSION

In-plane tensile test after heating and simulation analysis were conducted to determine the structured performances of SCCV with openings under SA. The test results reveal that the verge of the reinforced openings did not rupture at the tensile yield level of the general parts of the steel plate and that the tensile strain of the verge had enough tolerance against yield strain in the event of an SA. Thus, the results confirmed that the adopted opening reinforcement method is appropriate. The simulation analysis was able to reproduce the individual test results almost exactly.

ACKNOWLEDGEMENTS

This work was mainly carried out during FY2011-2016 as Japan national project “Development of Integrity Evaluation Method for PCV Structure” with the participation of The Chugoku Electric Power Company, Inc., Tohoku Electric Power Company, Inc., Tokyo Electric Power Company, Inc., Chubu Electric Power Company, Inc., Hokuriku Electric Power Company, Inc., The Japan Atomic Power Company, Electric Power Development Company, Ltd., the Institute of Applied Energy, Toshiba Corporation and Hitachi-GE Nuclear Energy, Ltd.

We would like to thank Dr. T. Nishikawa, a Professor Emeritus at Tokyo Metropolitan University, Dr. K. Takiguchi, a Professor Emeritus at Tokyo Institute of Technology, Dr. I. Maruyama, a Professor at Nagoya University, and Dr. Y. Kitsutaka, a Professor at Tokyo Metropolitan University for valuable discussions.

REFERENCE

1) The Japan Society of Mechanical Engineers: Codes for Nuclear Power Generation Facilities (2008) - Rules on Design and Construction for Nuclear Power Plants -.