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Division VI

APPLICABILITY EVALUATION OF STEEL PLATE REINFORCED CONCRETE STRUCTURE TO PRIMARY CONTAINMENT VESSEL OF BWRS

(8) SHEAR LOADING TEST OF STEEL PLATE REINFORCED CONCRETE STRUCTURE UNDER HIGH TEMPERATURE CONDITIONS

Yasumi Kitajima[1], Masashi Tanabe[2], Shizuka Hirako[3], Toshihiko Hirama[4], Hitoshi Kumagai[5], and Tetsuo Abiru[6]

[1] Senior Specialist, Toshiba Corporation, Japan
[2] Specialist, Toshiba Corporation, Japan
[3] Senior Engineer, Hitachi-GE Nuclear Energy, Japan
[4] Senior Engineer, Shimizu Corporation, Japan
[5] Chief Research Engineer, Shimizu Corporation, Japan
[6] Manager, The Chugoku Electric Power, Japan

ABSTRACT

In-plain shear loading tests were conducted to evaluate the seismic safety of steel plate reinforced concrete containment vessel (SCCV) under high temperature and high pressure conditions assuming severe accident. The wall-shaped specimens were downsized to object a part of SCCV. The test parameters were maximum temperatures, heating duration, initial membrane force and loading hysteresis (monotonic or reverse cyclic). The both faces of steel plate were heated up to 145, 175, 200 and 300 °C in each case. When the temperature had reached target value, membrane force was introduced, and then in-plane shear force was applied. Simulation analysis using elastic-plastic finite element analysis code was performed to evaluate the test results. In the analysis, reduction factors due to high temperature for young’s modulus, compressive strength of concrete and yield stress of steel were considered. The reduction factors prescribed in Eurocode or JSME standard were applied, because their applicability was previously confirmed by the material test.

INTRODUCTION

The primary containment vessel (PCV) is a critical component of nuclear power plants which contains radioactive materials inside it in case of accidents. The steel plate reinforced concrete (SC) structure is considered to be a candidate for PCVs of future nuclear power plants. However, it is required to confirm the applicability for basic performance of SC structure, especially the aseismatic and pressure-resistant performances under high temperature conditions to apply it to PCVs.

As part of basic study of this series1)-4), this paper describes shear loading tests and analyses conducted to obtain the properties of steel plate reinforced concrete (SC) structure with respect to in-plane shear force to evaluate the seismic safety of SCCV.

SHEAR LOADING TEST

Conditions and Cases

For the purpose of simulation and workability, the wall-shaped specimens were downsized to 1/7 of SCCV. Dimensions are shown in Table 1.

Table 1: Dimensions.

		SCCV	Test specimen	Ratio
Wall	Thickness: T	2000	285	1/7
Steel plate	Thickness: t	16	2.3	1/7
	t/T	0.008	0.008	-
Stud	Diameter: d	22~25	3.5	1/7
	Pitch: B	320	46	1/7
	B/t	20	20	-
	Length: L	176~200	28	1/7
	L/d	8	8	-
Concrete	Aggregate size	25	10	1/2.5

Unit: millimetre (for dimensions, MPa for strength)

The test parameters were temperatures, heating duration, initial membrane force and loading hysteresis (monotonic or reverse cyclic). The both faces of steel plate were heated up to 145, 175, 200 and 300 °C in each case to simulate the DBA (Design Base Accident) and SA (Severe Accident) conditions for SCCV. When the temperature had reached target value, membrane force was introduced, and then in-plane shear force was applied.

Table 2: Test cases.

No.	Temperature and heating duration	Membrane force	Loading hysteresis	
1	Room temperature	1600 kN	Monotonic	Operating time + seismic
2	Room temperature	None	Monotonic	Effect of axial tension
3	145 °C for 30 days	None	Monotonic	DBA + seismic
4	145 °C for 30 days	None	Cyclic	Effect of cyclic loading
5	175 °C for 60 min.	None	Monotonic	DBA + seismic
6	200 °C for 30 days	1600 kN	Monotonic	DBA (conservative assumption) + seismic
7	300 °C for 30 days	None	Monotonic	SA + seismic

Figure 3 shows the test specimen, which consists of 700 mm x 700 mm SC wall and 1840 x 650 stubs on both ends.

Test Method

In this test, each test specimen was first heated to the temperature noted in Table 2. After the duration also noted in Table 2, then in-plane shear force load (cyclic in case 4, monotonic in the other cases) was applied until it reached its ultimate strength.

Figure 4 shows the test apparatus. SC wall area was surrounded by panel heaters. It was set in frames, and 2 horizontal and 2 vertical jacks were set to apply tensile membrane force and in-plane shear force, respectively.

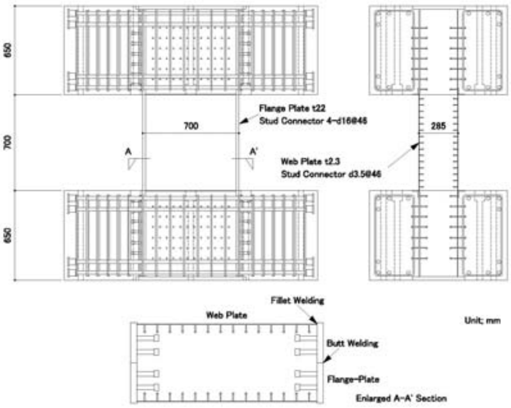


Figure 1. Test Specimen.

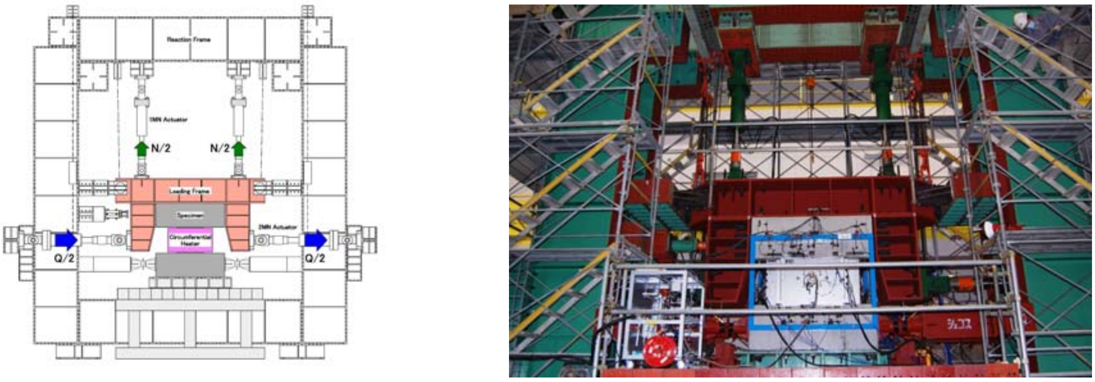


Figure 2. Test Apparatus.

Test Results

(1) Load vs Displacement

Table 3 shows the test results. Figure 3 and 4 show the relationship between load (sum of horizontal load) and displacement (horizontal displacement divided by wall height) for case No. 2 and comparison between case No. 3, and 4, respectively, Figure 5 shows the results for all cases.

The results show the strength of the SC wall decreased to 90 % for membrane force (case No.1) and 80 % for high temperature (case No. 3 to 6). Also, its initial stiffness decreased to 60 % for membrane force (case No.1) and 20 to 40 % for high temperature.

Table 3: Test results.

No.	Test Conditions	Compressive strength of concrete [N/mm2]	Initial stiffness [kN/mm]	Shear force at Yielding [kN]	Strength [kN]	Strength modified by concrete strength [kN]
1	Room Temperature Membrane force 1600kN	39.1	960	2555	2987	3021
2	Room Temperature	46.2	1541	3047	3512	3268
3	145 °C for 30 days	40.4	639	2099	2494	2482
4	145 °C for 30 days Cyclic Loading	47.8	547	2218	3107	2842
5	175 °C for 60 min.	42.3	489	2091	2668	2594
6	200 °C for 30 days Membrane force 1600kN	45.4	342	2044	2893	2716
7	300 °C for 30 days	37.7	440	1988	2709	2790

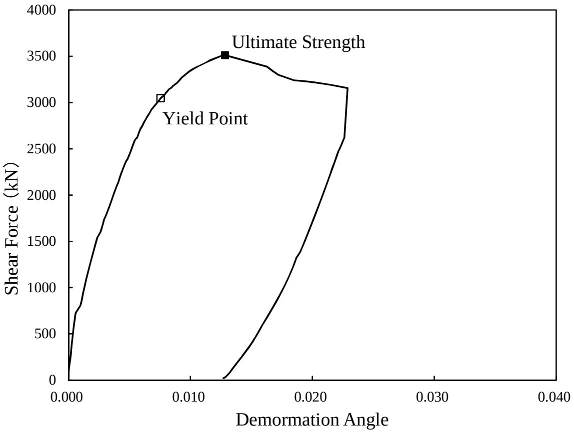


Figure 3. Shear Force vs Deformation Angle. (Case No.2)

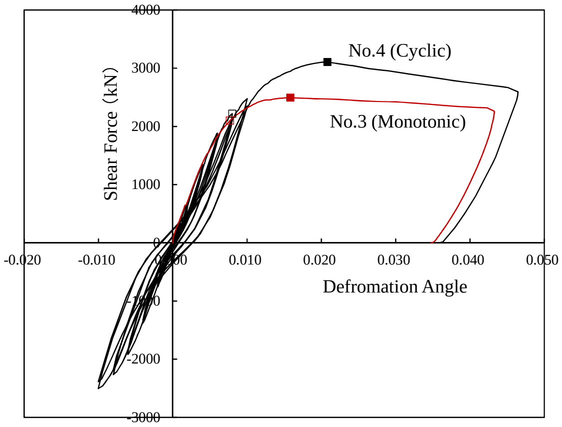


Figure 4. Shear Force vs Deformation Angle. (Case No, 3 and 4)

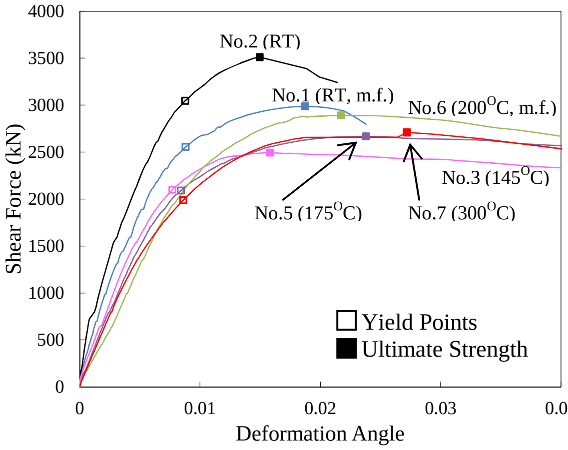


Figure 5. Shear Force vs Deformation Angle for all monotonic loading cases.

(2) Post test inspection

As Figure 6 and 7 show the post test inspection for the specimens for case No. 2 (at room temperature without membrane force) and case No. 6 (200 °C with membrane force). These figure show that there was no buckling nor crack on the steel plates. For the concrete, there were narrow cracks from the upper right corner to the lower left corner. It is considered that the specimens were under shear failure. Case No.4 (case for cyclic loading) also showed the similar results.

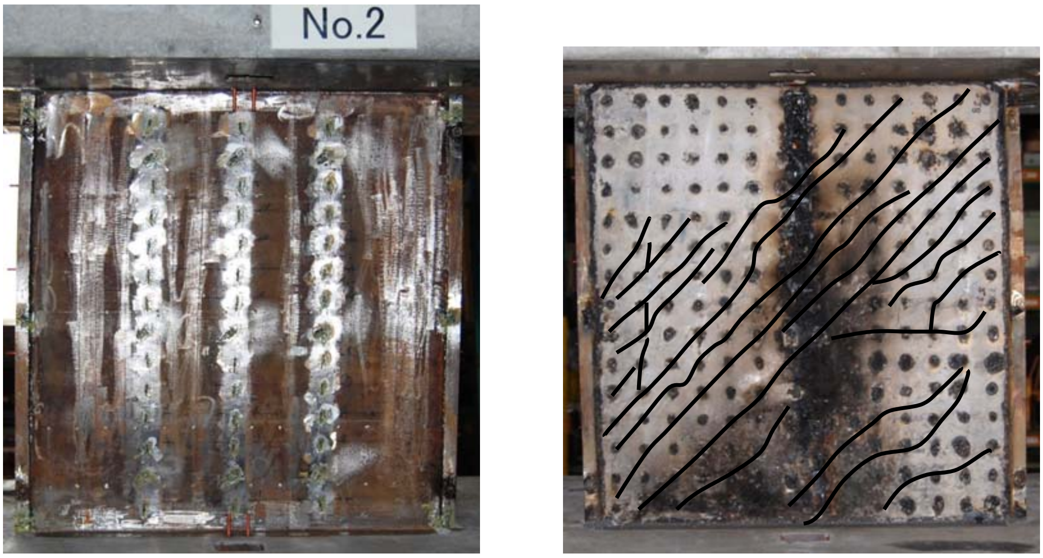


Figure 6. Steel plate and Concrete of post test inspection.
(Case No. 2 (Room temperature without membrane force))

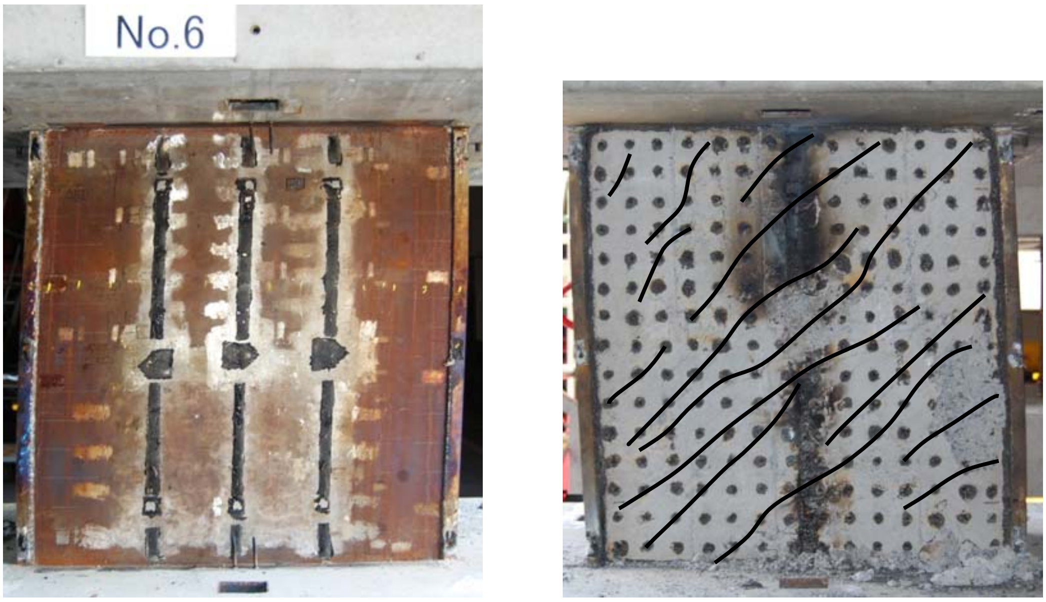


Figure 7. Steel plate and Concrete of post test inspection.
(Case No. 6 (200 °C with membrane force))

ANALYTICAL APPROACH

Analysis Model

We have also conducted FEM analyses to develop the simulation method for SC structure under shear force. For this purpose, we made 2 different types of analysis models. Detailed models were used to simulate the local phenomenon such as buckling and cracks, and simplified models were used to simulate the overall behaviour of SCCVs.

ABAQUS Standard Ver6.10 was used for analyses. To simulate the above-mentioned test, we first conducted heat transfer analysis until it reached target temperature, and then stress analysis for thermal and shear loading.

Figure 8 shows the detailed model. The model included the SC wall area and stubs, and utilized solid elements for steel plates and concrete, and spring elements for studs. Figure 9 shows the simplified model. It modelled only the SC area, and utilized shell elements for steel plate and concrete. Both modelled 1/2 area of test specimens for symmetry.

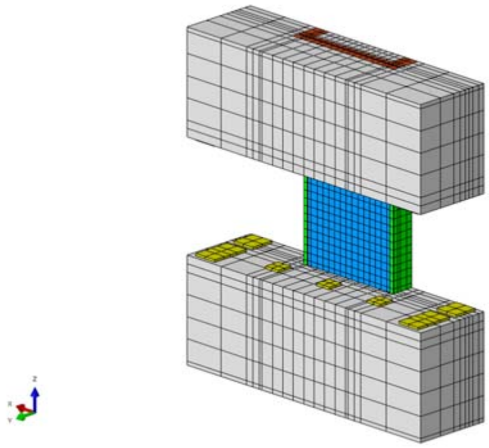


Figure 8. Mesh for detailed mode.

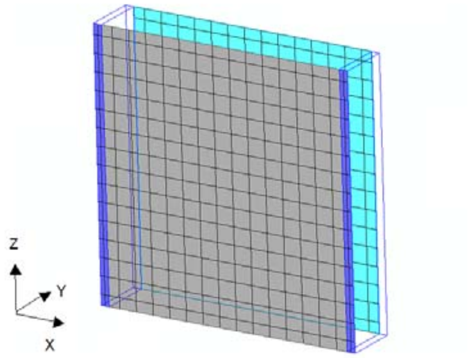
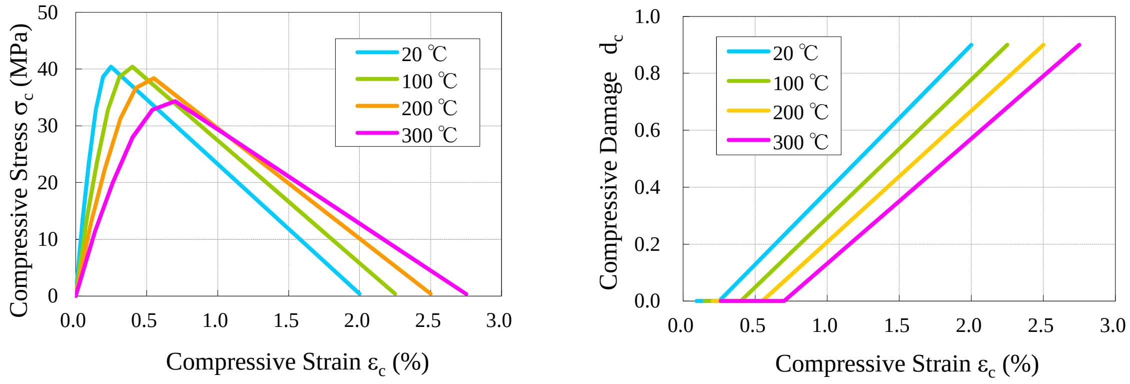


Figure 9. Mesh for simplified model.

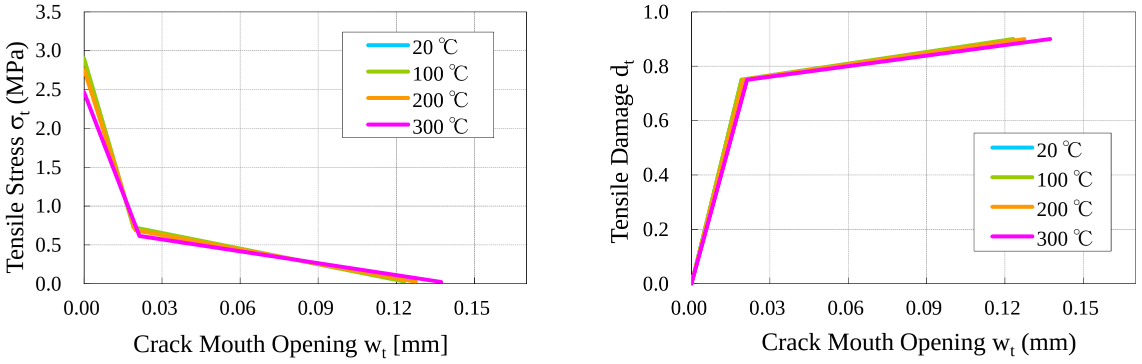
Analysis Method

We utilized thermal and mechanical properties for the analyses based on the basic test results[1)] and Eurocode[5), 6)]. Thermal conductivity, specific heat, thermal expansion, Young's modulus, Poisson's ratio and compressive stress-strain relationship for concrete were based on Eurocode. Tensile stress-cracking relationships for concrete were based on the model of Japan Society of Civil Engineers, but deceased strength was based on Eurocode and basic test results. Thermal expansion and Young's Modulus of steel were based on Japanese nuclear regulation. Stress-strain relationships of steel were based on the basic tests.

Figure 10 show the mechanical properties of concrete at higher temperature for the following analyses.



(a) Compressive Stress-Strain (b) Compressive damaged plasticity



(c) Tensile Stress-Cracking (d) Tensile damaged plasticity

Figure 10. Mechanical Properties for Concrete.

Analysis Results

Table 4 shows the analysis results. The results of detailed modes have good agreement with the test results. For the cases of high temperature (case No. 3, 5 and 6), analytical results of initial stiffness were slightly higher than that of tests. Numbers in parenthesis are ratio against the test results.

Table 4: Analysis results.

No.	Shear Force at Yielding [kN]			Ultimate Strength [kN]			Initial Stiffness	
	Detailed	Simplified	Test	Detailed	Simplified	Test	Detailed	Test
1	2477 (0.97)	2533 (0.99)	2555 -	2880 (0.96)	2533 (0.85)	2987 -	921 (0.96)	960 -
2	2624 (0.86)	2658 (0.87)	3047 -	3023 (0.86)	2658 (0.76)	3512 -	1634 (1.06)	1541 -
3	2193 (1.04)	2104 (1.00)	2099 -	2735 (1.10)	2361 (1.10)	2495 -	1011 (1.58)	639 -
5	2271 (1.09)	2171 (1.04)	2091 -	2709 (1.02)	2709 (1.02)	2668 -	984 (2.01)	489 -
6	2137 (1.05)	1988 (0.97)	2044 -	2597 (0.90)	2597 (0.90)	2893 -	811 (2.37)	342 -
7	2034 (1.02)	2180 (1.07)	1988 -	2891 (1.10)	2695 (0.99)	2709 -	880 (2.0)	440 -

Figure 11 and 12 show the comparison between analysis (utilized detailed models) and the test for case No. 2 and No. 3 and 4, respectively. Figure 13 and 14 show the comparison between analysis (utilized simplified models) and the test for case No. 2 and No. 3 and 4, respectively. Figure 15 and 16 show the results for all cases for detailed models and simplified models, respectively.

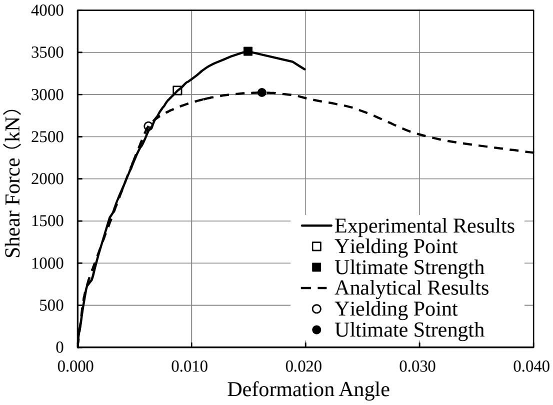


Figure 11. Shear force vs Deformation Angle. (Detailed, Case No.2)

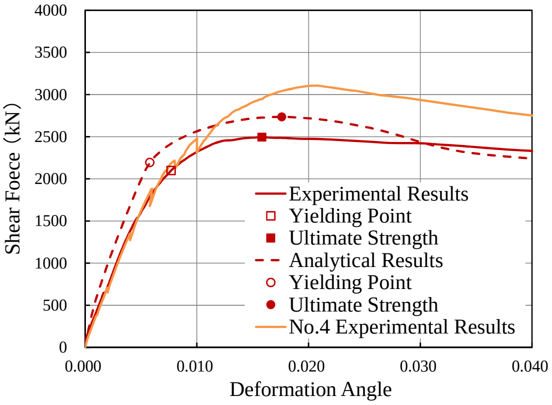


Figure 12. Shear force vs Deformation Angle. (Detailed, Case No.3)

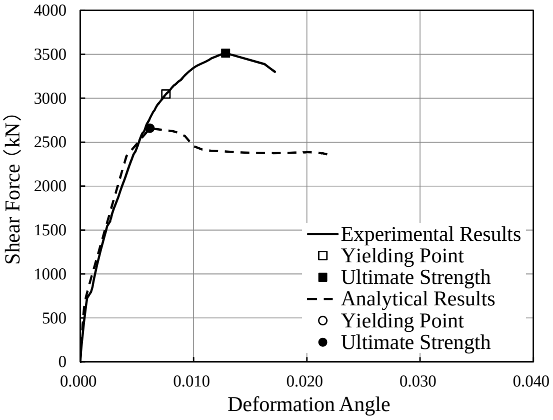


Figure 13. Shear force vs Deformation Angle. (Simplified, Case No.2)

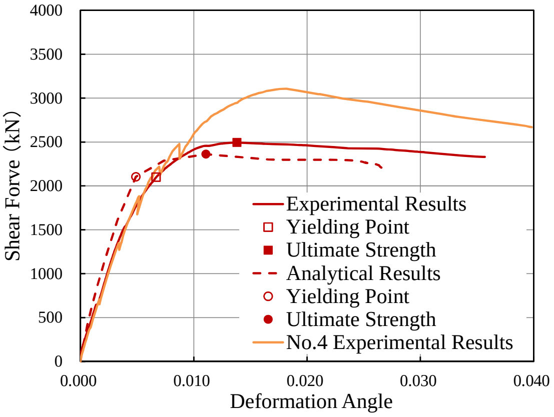


Figure 14. Shear force vs Deformation Angle. (Simplified, Case No.3)

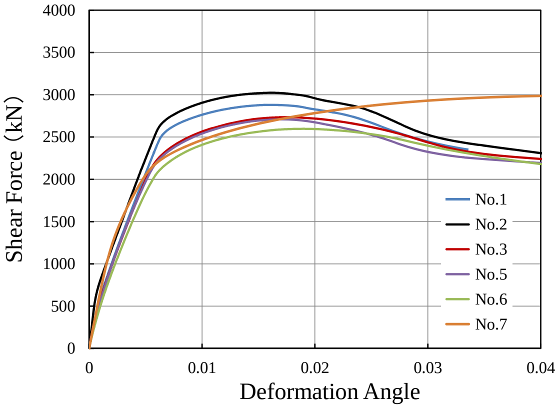


Figure 15. Shear force vs Deformation Angle. (Detailed, all cases)

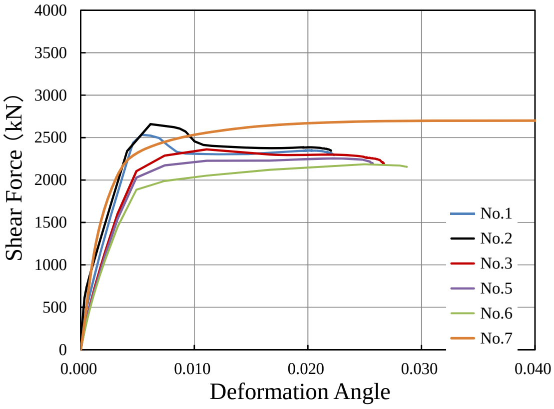


Figure 16. Shear force vs Deformation Angle. (Simplified, all cases)

CONCLUSION

To evaluate the applicability of SC to PCV of BWRs, we have conducted tests and analyses for SC structure subjected to shear loading under the high temperature condition.

Test results show the ultimate strength of the SC wall decreased to 90 % for membrane force and 80 % for high temperature. Also, its initial stiffness decreased to 60 % for membrane force and 20 to 40 % for high temperature. However, there was no buckling nor crack on the steel plates.

The analysis results show the applicability of FEM analysis with concrete models to simulate detailed and simplified behaviour of SC structure subjected to shear force under high temperature condition. However, FEM has the tendency to estimate initial stiffness of SC wall higher than the test results under high temperature conditions.

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