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APPLICABILITY EVALUATION OF STEEL PLATE REINFORCED CONCRETE STRUCTURE TO PRIMARY CONTAINMENT VESSEL OF BWRs (6) MECHANICAL AND THERMAL PROPERTIES OF STEEL UNDER HIGH TEMPERATURE UP TO 700°C

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ABSTRACT

In this study, mechanical (yield point strength, young's modulus, tensile strength) and thermal (thermal elongation) properties of steel under high temperature up to 700°C are obtained as the basic data necessary to evaluate the applicability of steel plate concrete containment vessel (SCCV) under high temperature. Steel plate, stud and reinforcing steel bar are tested as materials constituting SCCV. Two types of high yield strength steel plates are used as steel plate specimens. Headed studs (22 mm diameter) and deformed bars (51 mm diameter) are used as stud specimens and reinforcing steel bar specimens, respectively. Mechanical properties of steel decrease with increase in temperature, especially degradation over 400°C is significant. Thermal elongation of all types of specimens increases almost linearly with increase in temperature. These results are compared with the existing codes (Eurocode and JSME: Japanese design code for nuclear power generation facilities) and the differences among them are highlighted.

INTRODUCTION

The Research & Development of a primary containment vessel with a steel plate reinforced concrete structure (SC structure) has been proceeded. [1] As previously reported, we conducted the material tests of steel (steel plate, stud and reinforcing steel bar) at high temperature to sophisticate the structural integrity evaluation method and to establish an analysis technique of a steel plate reinforced concrete containment vessel at severe accident temperature. [2] Based on Fukushima Daiichi Accident, we target the basic data upgraded for structural integrity evaluation of a steel plate reinforced concrete containment vessel (SCCV) in higher temperature range. In this report, mechanical and thermal properties of steel under high temperature up to 700°C are obtained.

TEST SPECIMENS

Table 1 shows a list of test specimens shapes, numbers, and applied standards in tensile test. And Table 2 shows a list of test specimens shapes, numbers, and applied standards in thermal elongation test.
Since both of full-SC structure and half-SC structure in combination with reinforced concrete structure are applied for SCCV, the material tests under elevated temperature were conducted on steel plate, stud connector and reinforcing steel bar.
Tensile test (yield point strength, young's modulus, tensile strength) and thermal elongation test were conducted at temperature ranging from room to high temperature 700°C.
For Young's modulus measurement, we also conducted by the resonance method.

Table 1 Tensile test specimens

Test case		Thickness /Diameter	Number	Test specimens shapes
Steel plate (SPV490)	Rolling direction	PL-6	18	Collared test specimens plate (JIS G 0567 appendix A A. 5)
	Rolling orthogonal direction	PL-6	9	
Steel plate (SHY685)	Rolling direction	PL-9	3	Room temperature test specimens plate
		PL-5	18	Collared test specimens plate (JIS G 0567 appendix A A. 5)
	Rolling orthogonal direction	PL-5	9	
Stud connector (SWCH16A)		ϕ 10	18	Collared test specimens plate (JIS G 0567 appendix A A. 5)
Reinforced steel bar (SD390)		ϕ 10	18	Collared test specimens plate (JIS G 0567 appendix A A. 5)

Table 2 Thermal elongation test specimens

Steel material	Diameter	Number	Test specimens shapes
Steel plate (SPV490)	ϕ 5	3	Diameter 5mm, Length 20mm (Based on JIS Z 2285)
Steel plate (SHY685)	ϕ 5	3	Diameter 5mm, Length 20mm (Based on JIS Z 2285)
Stud connecter	ϕ 5	3	Diameter 5mm, Length 20mm (Based on JIS Z 2285)
Reinforcing steel (SD390)	ϕ 5	3	Diameter 5mm, Length 20mm (Based on JIS Z 2285)

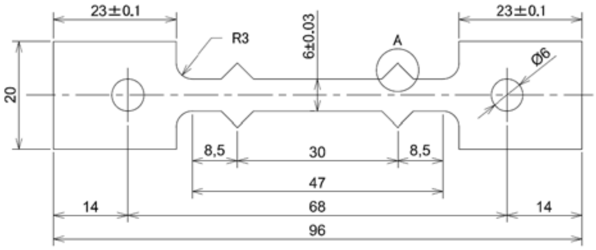

Figure 1 High temperature tensile test specimens plate

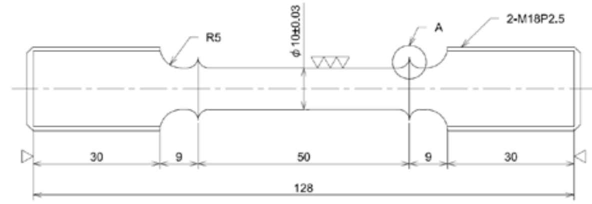

Figure 2 High temperature tensile test specimens rod

TENSILE TEST

To obtain mechanical properties at accident temperature, we conducted tensile tests of steel plate, stud and reinforcing steel bar. The one of the used plates is called SPV490, which is Japan Industrial Standard (JIS) G3115 for steel plate of pressure vessel. The other is called SHY685, which is one of high-tensile steel with a high-yield-point for welded structures. In the tensile test of steel plate for pressure vessel, we should consider the effect of cut-out direction of specimen, such as the rolling direction and the direction perpendicular to the rolling of the steel plate, and the effect of planning work, which is done to decrease the thickness of plate to be used as specimen, on the tensile test results in order to use the results for evaluation of various test results and simulation analysis as well. Therefore, we reflected them in the test cases.

SPV490 was kept in original thickness, and SHY685 was cut down to 5 mm, and then, they were shaped as shown in Figure 1. The test specimen of stud connector and reinforced steel bar were shaped as shown in Figure 2.

The temperature parameter in tensile test is shown in Table 3. In steel plate, stud connector and reinforcing steel bar test, we obtain yield point, tensile strength, young’s modulus, and stress-strain relation. The number of specimens was to be three for the combination of each test condition. The tensile test procedure of steel plate, stud connector and reinforcing steel bar is based on JIS G 0567 “High temperature tensile test method for steel materials and heat resistant alloys”, and load the monotonic tensile by using the universal testing machine with electric furnace. The holding time is set in around 15 minutes till the starting time of the test since it reaches the required temperature for the test.

Table 3 Temperature parameter
(Steel plate, stud connector and reinforcing steel bar)

Item	Test parameter
Heating temperature	20°C, 150°C 200°C , 300°C , 500°C , 700°C

THERMAL ELONGATION TEST

To obtain thermal properties at accident temperature, we conducted thermal elongation tests of steel plate, stud and reinforcing steel bar. The temperature parameter in thermal elongation test is shown in Table 4. The thermal elongation test procedure of steel plate, stud connector and reinforcing steel bar is based on JIS Z 2285 "Method for measuring linear expansion coefficient of metal material". The thermal elongation test specimen was shaped in column as shown in Table 2. In the thermal test, obtaining the data up to about 800°C, we report it.

Table 4 Temperature parameter
(Steel plate, stud connector and reinforcing steel bar)

Item	Test parameter
Heating temperature	30°C ~700°C

RESULT AND DISCUSSION

Tensile test

・Yield point strength residual ratio

Figure 5 shows the relation of the yield point strength residual ratio of SPV490 steel plate, and SHY685 steel plate to JSME S NC1 - 2008[3] (called JSME) and Eurocode[4]. The yield point residual ratio of steel plate shows tendency of decrease in accordance with the temperature increase. The ratio of SPV490 steel plate and SHY685 steel plate is higher than JSME value (up to 375°C), and lower than Eurocode value (up to 800°C). There is no difference depending on the material type.

Figure 6 shows the relation of the yield point strength residual ratio of stud connector, and reinforcing steel bar to Eurocode. The yield point strength residual ratio of stud connector remains the value of room till the temperature gets up to 300°C without decrease, but shows the remarkable decreasing after it reach over 500°C. This tendency corresponds roughly to the Eurocode tendency. On the other hands, the yield point strength residual ratio of reinforced steel bar shows tendency to decrease with increasing temperature, and is lower in all the temperature ranges than Eurocode values.

・Tensile strength residual ratio

Figure 7 shows the relation of the tensile strength residual ratio of SPV490 steel plate and SHY685 steel plate to JSME. On tensile strength residual ratio of steel plate, both of SPV490 steel plate and SHY685 steel plate remains almost the value of room till the temperature gets up to 300°C without decrease, and shows the remarkable decreasing from 500°C, and it is higher than JSME value (up to 375°C). There is no difference depending on the material type.

The tensile strength residual ratio of stud connector and reinforced steel bar is shown in Figure 8. The values of stud connector and reinforced steel bar firstly rise up in 200~ 300°C, and then, it shows remarkable decreasing. Increase at 200 to 300 ° C is thought to be caused by blue heat embrittlement.

・Young's modulus residual ratio

Figure 9 shows the relation of the Young's modulus residual ratio of SPV490 steel plate and SHY685 steel plate to JSME, and Eurocode. Young's modulus obtained from high temperature steel plate tensile test, although it is inconsistent, shows tendency of decrease in accordance with the temperature increase, and both of SPV490 steel plate and SHY685 steel plate corresponds averagely to the JSME value till it is 375°C. Till it gets up to 800°C, Eurocode value corresponds mostly to the minimum test value.

The young's modulus obtained by the resonance method is shown in Figure 10. The values by the resonance method are less inconsistent, and its decreasing tendency in accordance with the temperature corresponds greatly to JSME values (up to 375°C). There is no difference depending on the material type.
The young' modulus residual ratio of stud connector and reinforced steel bar is shown in Figure 11, and the result obtained by the resonance method is in Figure 12. The young's modulus residual ratio of stud connector and reinforced steel bar, in both of high temperature tensile test and the resonance method, shows tendency to decrease, and is higher than Eurocode values in all temperature range. On either steel materials, The young's modulus residual ratio obtained by the resonance method is slightly higher than the ratio obtained by high temperature tensile test.

Thermal elongation test

・Thermal elongation
Figure 13 shows the relation of the thermal elongation of SPV490 steel plate and SHY685 steel plate to JSME and Eurocode. The thermal elongations of steel plate rise almost linearly as the temperature rises up to 700 °C. Both of SPV490 steel plate and SHY685 steel plate largely correspond to JSME (up to 300°C), and Eurocode (up to 800°C). There is no difference depending on the material type.
The thermal elongation of stud connector and reinforced steel bar is shown in Figure 14. The thermal elongation of stud connector and reinforced steel bar also rises linearly up to 700 °C in accordance with temperature increase, and greatly corresponds to Eurocode tendency.

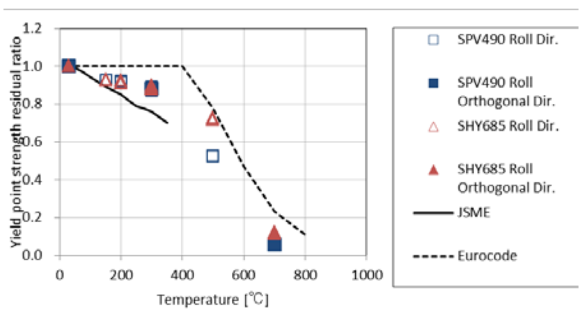

Figure 5 Yield point strength residual ratio
(Steel plate)

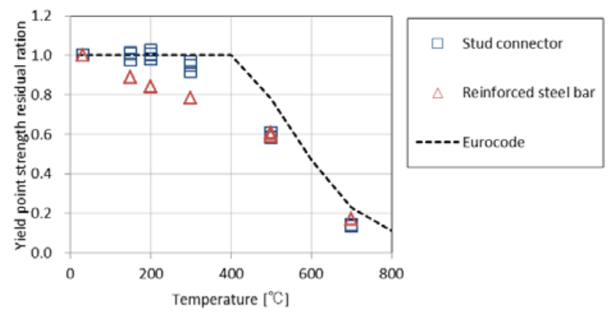

Figure 6 Yield point strength residual ratio
(Stud connector, Reinforced steel bar)

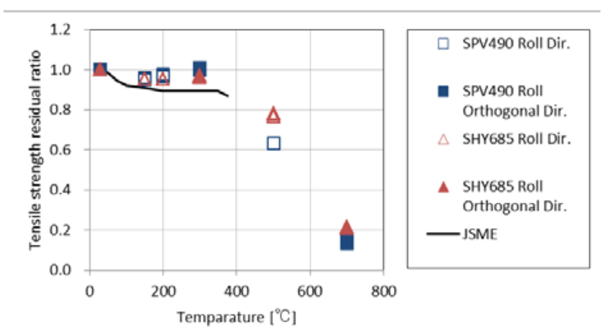

Figure 7 Tensile strength residual ratio
(Steel plate)

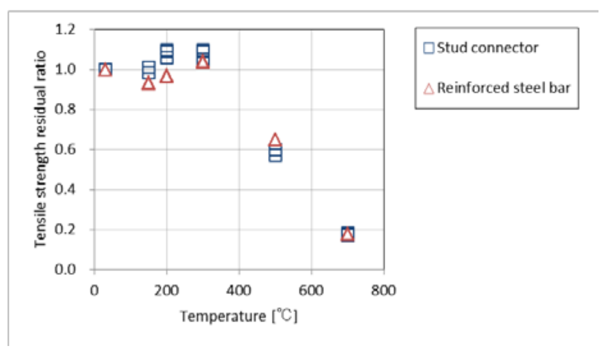

Figure 8 Tensile strength residual ratio
(Stud connector, Reinforced steel bar)

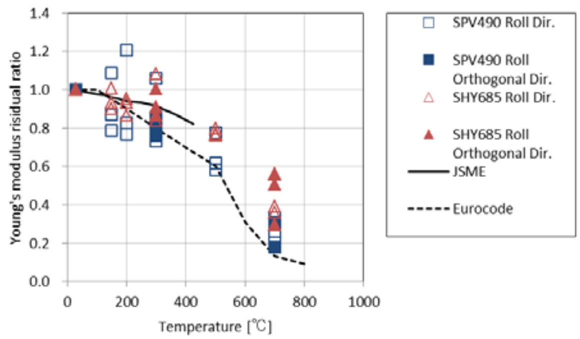

Figure 9 Young’s modulus residual ratio
(Steel plate)

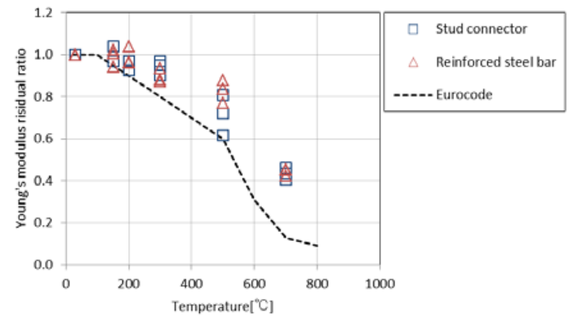

Figure 10 Young’s modulus residual ratio
(Stud connector, Reinforced steel bar)

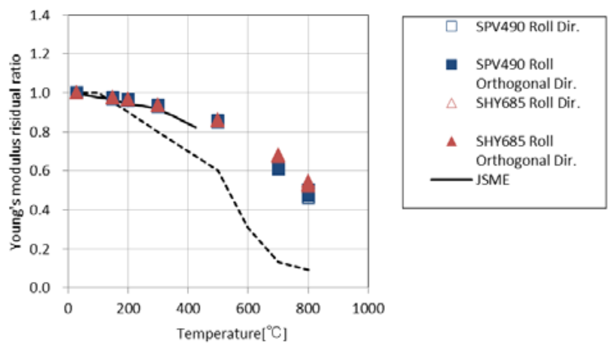

Figure 11 Young’s modulus residual ratio
-the resonance method-
(Steel plate)

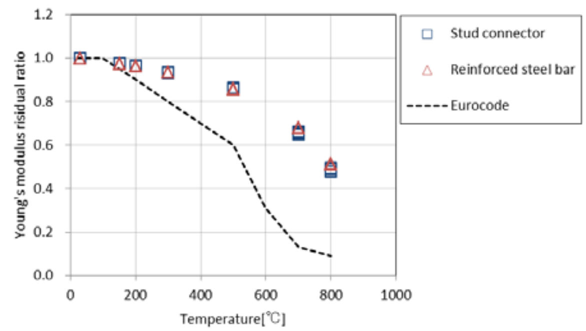

Figure 12 Young’s modulus residual ratio
-the resonance method-
(Stud connector, Reinforced steel bar)

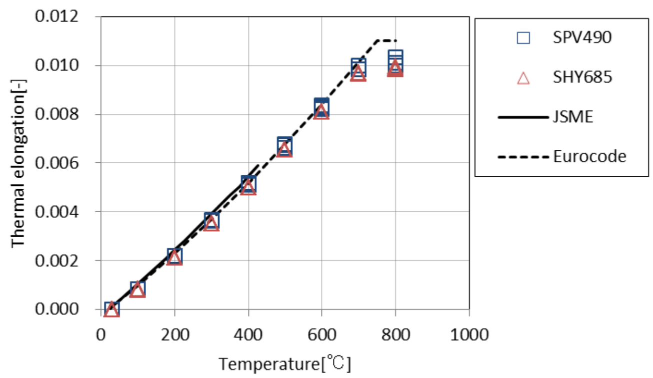

Figure 13 Thermal elongation
(Steel plate)

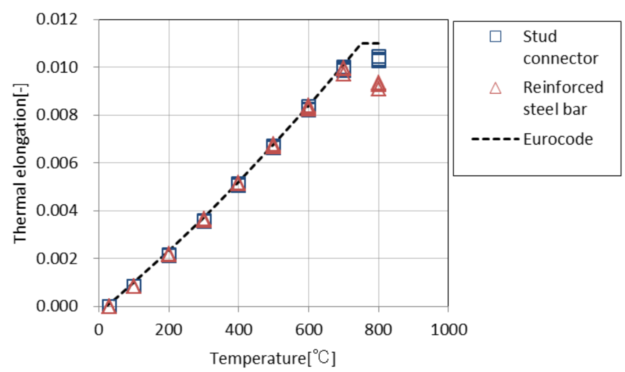

Figure 14 Thermal elongation
(Stud connector, Reinforced steel bar)

CONCLUSION

For steel materials (steel plate, stud connector, reinforcing steel bar) that make up the BWR containment vessel, we obtained mechanical and thermal properties under high temperature conditions in the severe accident. The mechanical and thermal tendencies of each steel material were grasped, which shall be the basic data showing the structural feasibility of SCCV. Details are shown below.

Steel plate

・All of the yield point strength, Young’s modulus and tensile strength residual ratio shows a tendency of decrease in accordance with the temperature increase.

・The tendency of decrease in the yield point strength residual ratio shows the intermediate tendency between JSME value and Eurocode in the range up to 300 ° C.

・The decrease in Young's modulus shows a tendency to generally correspond to the JSME value in the range up to 300°C.

Stud connector

・In the range up to 300 ° C, the yield point strength and tensile strength residual ratio shows no tendency of decrease.

・The decreasing tendency of Young's modulus is less noticeable than that of Eurocode.

Reinforcing steel bar

・The yield point strength decreases in accordance with the temperature increase, and the tendency of decrease is more pronounced than Eurocode. In the range up to 300°C, the tensile strength residual ratio shows no tendency of decrease.

・The Young's modulus is less noticeable than that of Eurocode.

Thermal Elongation

・All of the steel plate, the studs and the reinforcing bars showed an increase in thermal elongation, which corresponded to JSME value and Eurocode, and showed a tendency to linearly increase as the temperature increased up to 700°C.

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