EXPERIMENTAL AND FEASIBILITY STUDY ON STEEL-PLATE-REINFORCED-CONCRETE CONTAINMENT VESSEL FOR JAPAN SODIUM-COOLED FAST REACTOR

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ABSTRACT

Japan Sodium-Cooled Fast Reactor (JSFR) adopts a new concept of a containment vessel called steel plate reinforced concrete containment vessel (SCCV). The SCCV is considered to be effective to shorten construction period thanks for elimination of rebar work at a site compared with applying the reinforced concrete CV. Other than this advantage, the SCCV achieves high quality in building structure, since steel structure parts can be fabricated at a factory prior to the site construction. Although the SC structure has been used for the buildings of LWR etc, it is important to investigate its characteristics under high temperature to adopt the SC structure to the JSFR CV. This paper mainly describes the design study and experiments to investigate potential characteristics of the SC structure under hypothetical sodium combustion in the CV.

INTRODUCTION

The Japan Sodium-cooled Fast Reactor (JSFR) which is investigated as a promising candidate in the “Fast Reactor Cycle Technology Development (FaCT)” project have adopted a steel plate reinforced concrete (SC) structure (Fig.1) not only as a reactor building but also as a containment vessel (SCCV) shown in Fig.2 from the viewpoint of shortening construction period by adopting modular construction. As for conventional buildings, the SC structure has been used for the radioactive waste disposal facility of a light water reactor (LWR) and the shielding wall of MONJU (prototype reactor in Japan). Although bearing strength of the SC structure was well investigated at ambient temperatures [1], its adoption as the containment vessel (CV) has two main problems to be cleared: 1) the SCCV shall withstand high temperatures and pressure as well as dead load and seismic force, 2) the SCCV shall prevent leakage of radioactive nuclides under these severe conditions. In the case of the LWR SCCV, its major design conditions are the maximum temperature of 171 degree-C and the pressure of 0.31 MPa [2], and its characteristics under these loads are under investigation. On the other hand, because coolant temperature of a fast reactor is higher than that of the LWR, JAEA has carried out design, experimental and analytical studies of the SC structure from 2007 FY [3].

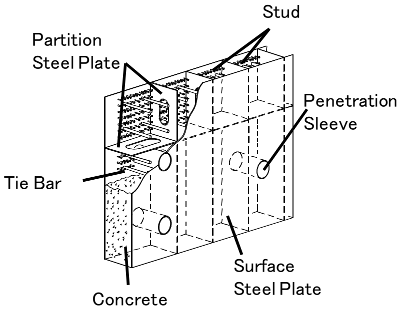


Fig.1 SC structure

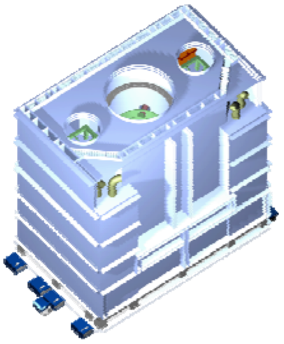


Fig.2 SCCV

DESIGN STUDY OF SCCV

A CV includes a reactor and a primary coolant system and it is a final barrier against leakage of radioactive nuclides. As for MONJU, its CV is a steel vessel and consists of a top hemi sphere, a central cylinder and a bottom shallow dish, with inside diameter of about 50 m and overall height of about 80 m. The CV of MONJU can maintain the structural integrity and the boundary function against temperatures and pressures in case of accidents such as the leakage of the primary coolant (Fig.3) [4]. Furthermore, the atmosphere around sodium contained equipments is nitrogen gas to prevent the combustion of sodium, and the large space filled with air atmosphere mitigates the influence of the pressure in case of accidents.

On the other hand, in the JSFR safety design, complete double wall structure for sodium contained components such as double-walled pipes of coolant and the guard vessel for the reactor vessel is adopted to prevent the combustion of leaked sodium in the CV (Fig.4) [5]. Furthermore, severe mechanical energy release due to re-criticality events can be eliminated from Core Disruptive Accident (CDA) scenarios by some safety design such as special fuel assembly features for molten fuel discharge from the core in case of CDA as well as the limitation of the core sodium void worth, multi-layered structure at the bottom of the reactor vessel for core debris retention within the reactor vessel. These design features reduce loads on the CV significantly and allow compact containment design. Since these design approaches prevent the combustion of the sodium in the CV, the influence of pressure caused by the sodium combustion is able to be excluded in the design of the JSFR CV. Hence the design pressure of the CV is lower than that of LWR, JSFR adopts the rectangular shape CV consisted of the SC structure to achieve economies by eliminating of the layout dead space and shortening the construction period.

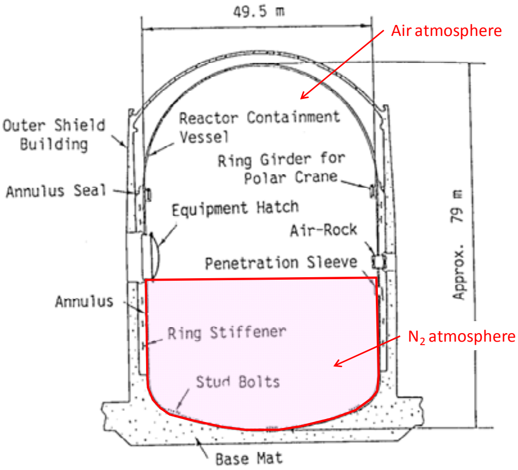


Fig.3 CV of MONJU

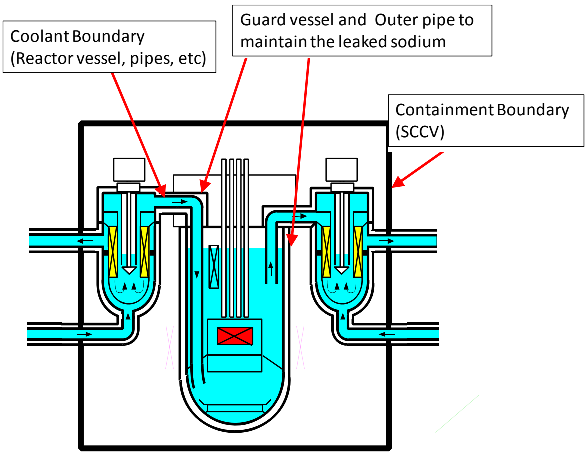


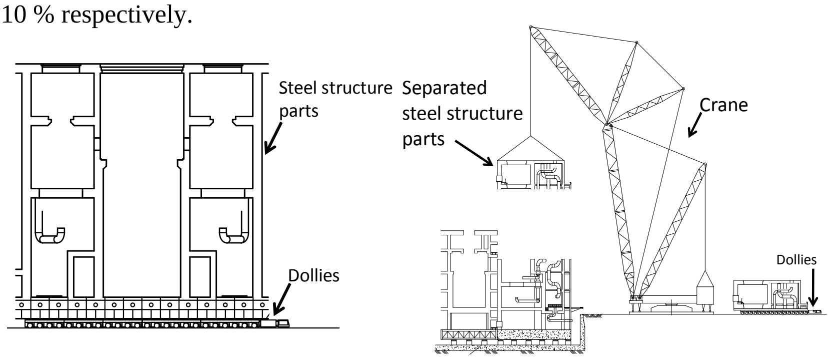
Fig.4 Double boundary design in JSFR

Effect of the modular construction on construction period

From the viewpoint of shortening the construction period and quality assurance of steel structure products, JSFR adopts the modular construction. In the outline of this method, the steel structure parts of the module are firstly assembled in a factory. Then some of components including ducts, pipes, cable trays and so on are installed in advance. Inspections of welds are also performed in the factory to assure its high quality since they become the boundary of the containment vessel. On the other hand, large size or heavy components such as the reactor vessel (RV), steam generator (SG) etc. are separately delivered to the construction site after assembling and inspections. Depending on the component and equipment configuration in building layout, the reactor building is divided into several modular units. The assembled steel modules are shipped by the barge from the factory to the site dock. After lying alongside the site dock, they are transported by several dollies and put on the top of seismic isolators which have been installed beforehand at the site. After the placing and hardening of concrete, the installation of the aforementioned large-sized heavy components is started.

However, since the reactor building is installed on a bed rock from the viewpoint of earthquake resistance, the surface stratum from the ground surface level to the bed rock should be excavated. The level difference between the ground surface and the bed rock, which depends on a site, influences the installation of modular units because the inclination of the installation road is within 3 % based on the practical performance of the dollies. If the level difference is large, the slope area (including the installation road and slopes on either sides of it) for the reactor building installation interferes the surrounding buildings (buildings of the turbine, waste storage, etc.). Hence, that causes the possibility of the interference of the construction or the additional increase of the amount of excavation, which is not preferable from the economical point of view. Accordingly, the installation of modular units by cranes is also considered in the construction period study. Figure 5 shows the installation concept of the construction method. If the dollies are used for the installation, the reactor building of the demonstration reactor of JSFR (750 MWe) is divided into 9 units (Fig.6) concerning about the composition of the equipments and the restriction of the transportability. On the other hand, if the cranes are used, the modular units are divided into 48 units.

The construction periods of JSFR demonstration reactor are shown in Fig.7. The construction period consists of the base mat work, the installation of seismic isolators, the architecture work of operation floor, the architecture work of reactor building, the equipments installation, the equipments and system operation test and the commissioning. In the conventional construction method, the reactor building and the CV are constructed by the reinforced concrete (RC) structure, and the SC structure is used only for walls around reactor vessel (RV). The works of reinforcing bar installation are necessary at a construction site. Regarding the effect of the SC structure in assembly work in the factory, architecture work may reduce to about half of its work in conventional RC construction way. Furthermore, it is practicable to start the architecture work partly because of the division of modular units. Based on the module design study, the late thirties months can be achieved. Compared with the conventional construction, the modular construction schedule by dollies and by cranes could reduce by 20 % and 10 % respectively.



Sallow rock level (transport by dollies) *Deep rock level (transport by Cranes)*

Fig.5 Modular construction

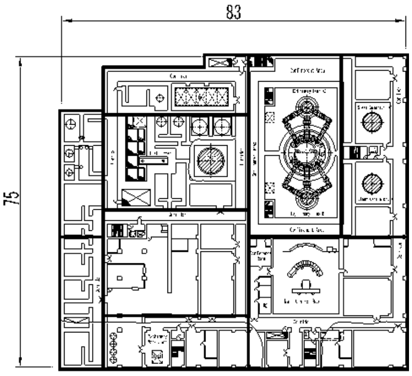


Fig.6 Divided units (transport by dollies)

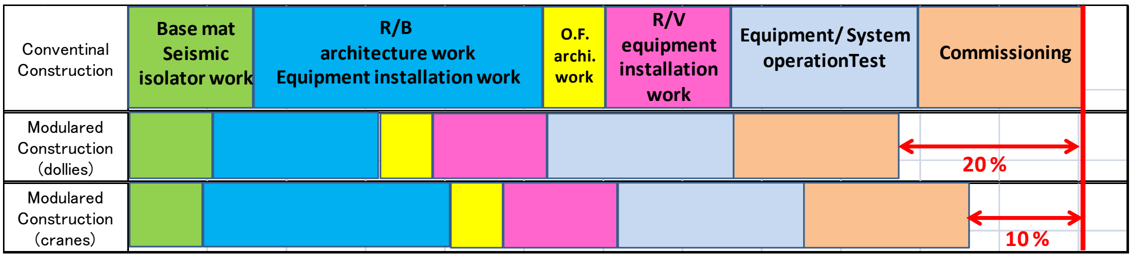


Fig.7 Construction periods

Loads for the SCCV

As mentioned above, since JSFR adopts the complete double wall structure for sodium contained equipments to prevent the combustion of leaked sodium in the CV, the sodium leakage accident is able to be excluded from design-basis events (DBEs). To assume loads for the SCCV in the DBE condition, the following conditions are selected; 1) Heat generation of gaseous and volatile radioactive materials inside the containment (100% inventory of noble gas and 10% Iodine etc. are assumed), 2) Heat radiated from sodium-containing components and piping without ventilation and cooling of the containment atmosphere in case of the containment isolation and 3) Low ambient pressure due to conservative meteorological condition. As a result of the analyses, the design loads for the SCCV at DBEs becomes less than 200 degree-C and 50kPaG.

In addition to the design basis approach, the SCCV must explicitly provide the containment (boundary) function against severe accidents. Such conditions for extended safety design are defined as Design Extension Conditions (DECs) [6]. However, JSFR safety design such as the double wall structure against sodium leakage, some countermeasures against severe re-criticality events could achieve prevention and mitigation against the typical DECs. For this reason, the loads for the SCCV at DECs are not dominant in the SCCV design. In spite of technical prevention of the combustion of sodium in the SCCV at DBEs and DECs, the hypothetical sodium leakage into the SCCV should be considered because it is the final barrier against the leakage of the radioactive nuclides. In this condition, the hypothetical sodium leakage and combustions by sodium spray and pool fire are considered. The leakage rate of sodium spray from branch pipe on the outer pipe is assumed up to a few kg/sec., and the maximum amount of sodium is about 160 ton which is assumed concerning the configuration of sodium-containing equipment. As a result of hypothetical evaluation, the temperature of the inner steel plate reaches 700 degree-C, where it continues for 20 minutes (Fig.8), and the maximum pressure reaches 120 kPaG for a moment.

Specification

Table 1 shows tentative design specifications of the SCCV. Although they were set in accordance with the JEAC4618 [7] which is the standard for the SC structure in Japan, the specifications of the inner plate shown in Table 1 are different from the JEAC4618. In case of the hypothetical sodium leakage, the inner plate is exposed to high temperatures over applicable range of rolled carbon steels for welded structure. For this reason, the carbon steel plate for pressure vessels for intermediate and moderate temperature services was used in the material of the inner plate. This full SC structure (Fig.1) would be adopted as bearing walls and floor deck, and the half SC structure would be adopted as top floor which has less influence of the sodium combustion.

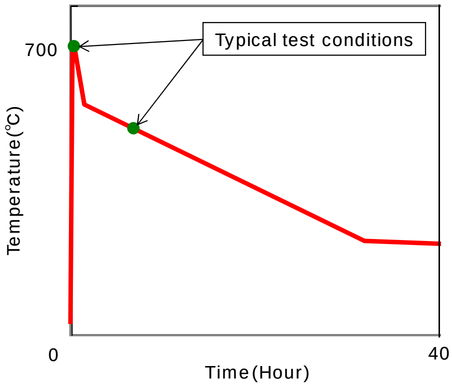


Fig.8 Temperature at inner plate
(Hypothetical condition)

Table 1 Tentative specifications of the SCCV

	SC wall thickness	1500 mm
Concrete	Design strength	21 ≤ Fc ≤ 36 N/mm^2
Surface plate	Inner plate Material (TS*)	Carbon steel plate for pressure vessels for intermediate and moderate temperature services (410 N/mm^2)
	Outer plate Material (TS*)	Rolled carbon steel for welded structure (400-490 N/mm^2)
	Thickness	12 mm
Stud	Material (TS*)	Carbon steel bar (400 N/mm^2)
	Diameter/Pitch/ Length	22 mm/400 mm/176 mm (8 times a diameter)
Partition Plate	Material (TS*)	Rolled carbon steel for general structure (400-490 N/mm^2)
	Thickness	12 mm
Tie bar	Material (TS*)	Carbon steel deformed bar (345 N/mm^2)

** TS: Tensile strength*

Table 2 Experiments Outline

Purpose	Main Parameter of experiment	Use*			
		①	②	③	④
1.Structural integrity of the SCCV					
(1)Material property					
1)Steel property (pull-out, bending and creep strength)	Temperaure	○	○	○	○
2)Concrete property (tensile/compressive strength)	Temperaure	○	○	○	○
(2)Anchor strength of attached stud on concrete					
1)Tensile strength	Temperaure, Diameter of stud, Enmbedded depth of stud	○	○	○	○
2)Shear strength	Temperaure, Diameter of stud	○	○	○	○
(3)Load-displacement relation of the SC beam					
1)Out-of-plane shear strength	Temperaure, Reinforcement type(tie bar, partition plate), Reinforcement ratio	○	○		○
2)Out-of-plane bending strength	Structual type, Temperaure, Number of partitioning plate (single partition / multi partition), Restriction / non-restriction of initial thermal deformation	○	○		
3)In-plane behavior (strength against seismic load)	Temperaure	○	○		○
(4)Strength of specific parts					
1)Strength of beam which has penetration part	Temperaure	○	○		○
2)Strength of corner part	Temperaure	○	○		
(5)Function of steam releasing structure in concrete	Temperaure	○			
2.Boundary function of the SCCV					
(1)Behavior of heated plate (damage mode)	Temperaure	○		○	
(2)Critical strain at attaching portion of stud on plate	Temperaure, Diameter of stud	○		○	

*Test results are used mainly for;
① research the property of the SC structure under high temp.
② development of the analytical model to evaluate the structural integrity of the SCCV
③ development of the analytical model to evaluate the boundary function of the SCCV
④ construction of the bearing force evaluation formula in the design code

EXPERIMENT PLAN

The structural characteristics tests of the SCCV under the hypothetical sodium leakage and the combustion condition were planned to be investigated (Phase I; from 2007 to 2010 FY) to figure out the potential characteristics of the SCCV. Subsequently, the investigation of its characteristics under the loads of the DBEs is planned to prepare design standard (Phase II; from 2011 to 2015 FY). Table 2 shows the outline of experiments of phase I. The data obtained by each test were planned to be used for researching the characteristics of the SC structure under high temperature, development of the analytical model to evaluate the structural integrity and the boundary function of the SCCV, and the proposal of the bearing strength formula in the design standard.

Because of the adoption of the rectangular shape CV in JSFR, out of plane force on the SC structure becomes dominant. Since a shear failure causes drastic decrease of bearing strength of the SC structure, a shear failure must be avoided in the design of the SCCV to assure its structural integrity. On the other hand, a bending failure is acceptable due to gradual decrease of bearing strength. To assure that a bending failure precede a shear failure, shear strength shall be designed with some margin against bending strength. For this reason, out of plane shear strength and bending characteristics were investigated experimentally. In addition, in-plane characteristics should be also considered against earthquake. In this section, results of the load-displacement relation test of the SC beams are outlined.

Load-displacement relation of SC beams

Out of plane shear

In order to verify the influence of high temperature on the strength of the SC structure and to propose the estimation method of the bearing strength, the out-of-plane shear tests under high temperatures were carried out, of which parameters are the reinforcing type and amount as shown in Fig.9, and tests were carried out at several points of the transient temperatures shown in Fig.8. In this paragraph, the outline of the tie bar reinforcement type is introduced.

Figure 10 shows the failure mode of a specimen which is loaded under 700 degree-C. The shear crack between the load and the support point was observed, which was thought to be brittle failure by diagonal tensile force. Tie bars near the heating surface were yielded. Figure 11 shows the load-displacement curves of the SC beams with the same reinforcement ratio. The shear strength decreases as temperature increases. The displacements at the maximum loads are almost the same.

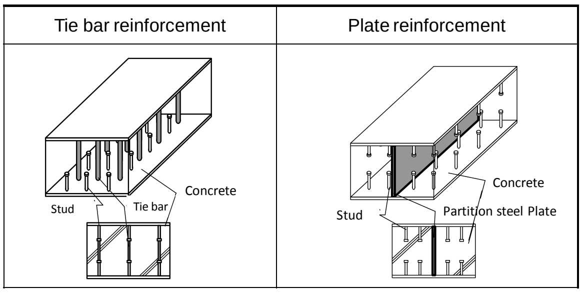


Fig.9 Reinforcement type of specimens

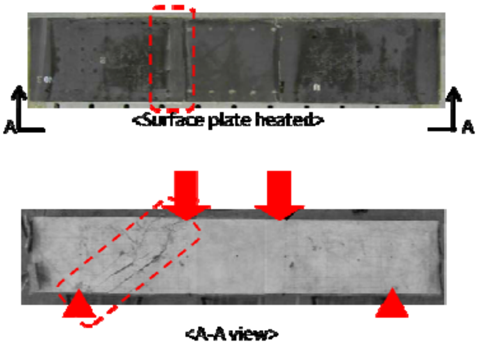


Fig.10 Failure mode (tie bar type, 700 degree-C)

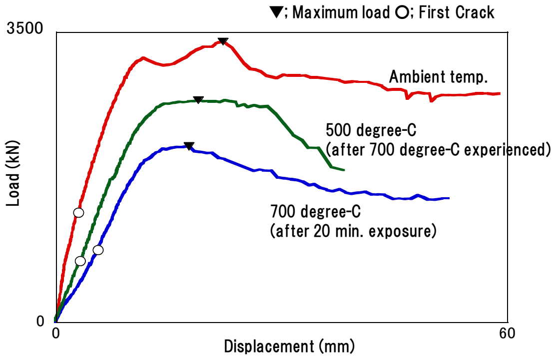


Fig.11 Load-displacement curves of the SC beams (tie bar reinforcement type)

Out of plane bending

A series of tests were carried out to verify 1) the influence of high temperature on the bending strength, 2) the influence of confined concrete between partition steel plates on the bearing strength (Fig.12) and 3) the influence of the restriction of initial thermal deformation on the specimen behavior (Fig. 13). Tests were carried out at several points of the transient temperatures (Fig.8).

Figure 14 shows the failure mode of the multi partition type specimen which is loaded under 500 degree-C after 700 degree-C experienced. The bending cracks near the tensile plate and crush of concrete near the compression plate were observed. Although the compression plate yielded and buckled, surface crack of the compression plate for the boundary of the SCCV was not observed. Figure 15 shows the bending load-displacement relationships. In this figure, “heated” means the loaded case under 500 degree-C after 700 degree-C experienced. “restrict” means the restriction of initial thermal deformation, as shown Fig.13. In order to directly compare the load-displacement relationships of the single partition with those of the multi partition which has five partition plates, the loads of the single partition are modified to be five times. From this figure, significant effect of confined concrete between partition plates is observed to raise bearing strength (comparison of case 1 with case 2). The load-displacement relationships of the multi partition are stable even in the large displacement region, compared with the single partition. The decrease of the bearing strength by high temperature was not observed clearly (comparison of case 2 with case 5). The restriction of initial thermal deformation during heating has little influence on the bearing strength in comparison with the non-restrict case (comparison of case 1 with case 3).

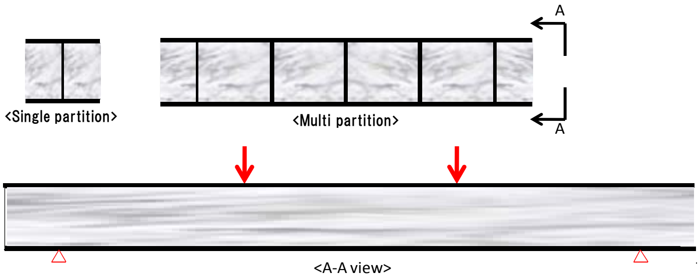


Fig.12 Specimens to verify the bounding effect of concrete

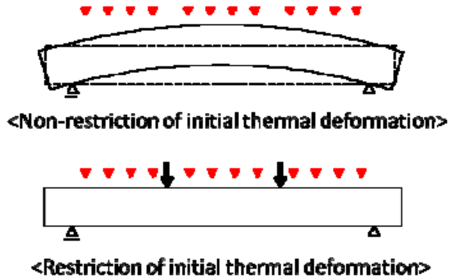


Fig.13 Restriction of initial thermal deformation

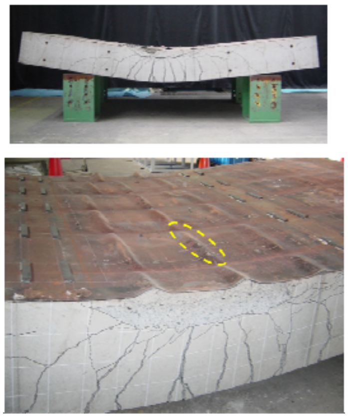


Fig.14 Failure mode of multi partition specimen

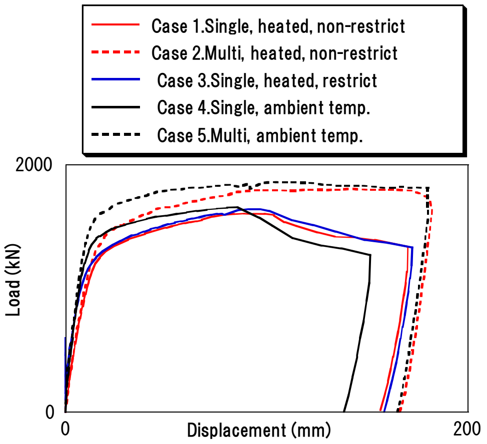


Fig.15 Load-displacement curves

In-plane behavior

In order to estimate the seismic in-plane shear strength after the experience of high temperature due to the hypothetical sodium leakage combustion and to verify the boundary condition of the heated surface, the lateral loading test shown Fig.16 was carried out. The static and cyclic in-plane force at the top of the specimen was gradually loaded when the specimen was cooled down to the ambient temperature after 700 degree-C experience, and the strain data on the surface plates were logged.

Figure 17 shows the load-shear strain curves, compared with the skeleton curve under ambient temperature described in JEAC4618 (ultimate shear strain: 6×10^{-3} rad), the drastic decrease of the load is not observed and the stable seismic behavior is expected. Even after the high temperature experience the specimen maintains higher strength than JEAC4618 shear strength formula under ambient temperature. Although the buckling in the surface plate occurred by the heat grew up as the lateral load were increased, surface cracks was not observed. As a result, high temperatures have little influence on in-plane shear characteristics and also on the boundary function.

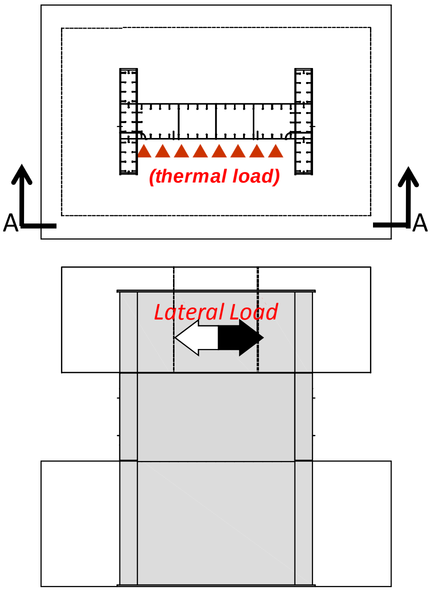


Fig.16 Specimen of the in-plane strength test

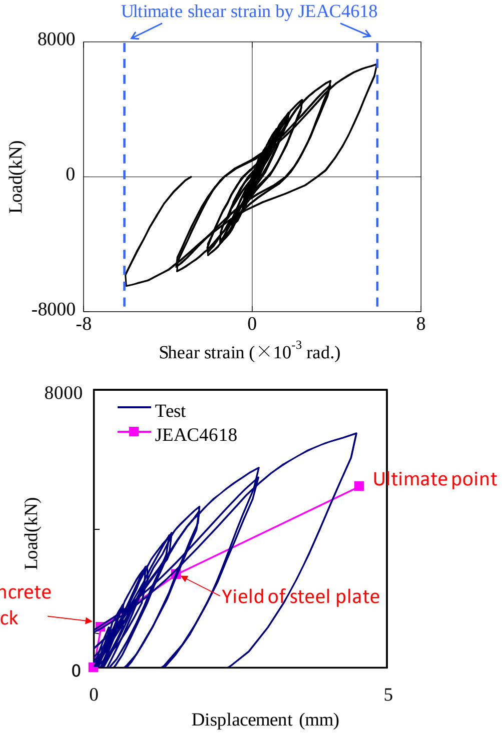


Fig.17 Load-Shear strain hysteresis curve

ANALYTICAL STUDY PHYLOSOPHY

The verification and validation for the structural integrity and the boundary function of the SCCV under the hypothetical sodium combustion are evaluated through analysis and test results. The evaluation of the SCCV behavior under high temperature consists of three parts; 1) heat transfer analysis, 2) stress analysis and 3) a crack generation and advance analysis of the boundary plate. Figure 18 shows an outline of these analyses. Based on the design loads of the SCCV described above, transient temperature distributions between surface plates are evaluated by the FEM model. In consideration of the evaluated transient temperature distribution, the stress analysis is also carried out by other FEM model (Fig.19). The data logged by the material property tests are applied in this model and the model is validated through the simulation analyses of the out-of-plane bending and shear tests, the bending tests of the corner part and the penetration part. The evaluated transient displacement of the SCCV is used for the boundary condition in the crack generation and advance analysis of the boundary plate. To evaluate the crack generation and advance, other FEM fine model is developed. These models are validated by the test results.

Based on these model developed, the behavior of the SCCV is evaluated from the viewpoints of structural integrity and boundary function. The structural integrity is confirmed by estimating compressive strain of concrete, tensile strain of plate, in-plane shear strength and out-of-plane shear strain. The boundary function is confirmed by evaluating local strain or steel crack depth. The criteria are mainly set up based on the test results.

CONCLUSION

JAEA has carried out design, experimental and analytical investigations of the SC structure to adopt it as the rectangular CV of JSFR. The experimental temperature conditions were set up concerning the DBEs and the hypothetical sodium leakage in the SCCV to verify its structural integrity and the boundary function. In a series of studies, the verification of the SCCV feasibility under the hypothetical sodium combustion was firstly planned to figure out the ultimate characteristics of the SCCV and to develop analytical model to evaluate the SCCV behavior.

From the design study, the construction periods of JSFR demonstration reactor are estimated concerning the bed rock level of the reactor building. As a result, it is cleared that the modular construction could reduce the construction period up to 20 % compared with the conventional construction.

In a series of experiments, characteristics of the SC structure (out-of-plane shear and bending behavior, in-plane behavior and so on) under the high temperature were investigated, and results of them were reflected for the development of the analysis method of the SCCV.

From 2011 FY, experimental studies about the behavior of the SCCV under DBEs condition are planned to be carried out to standardize the SCCV for the FR plant.

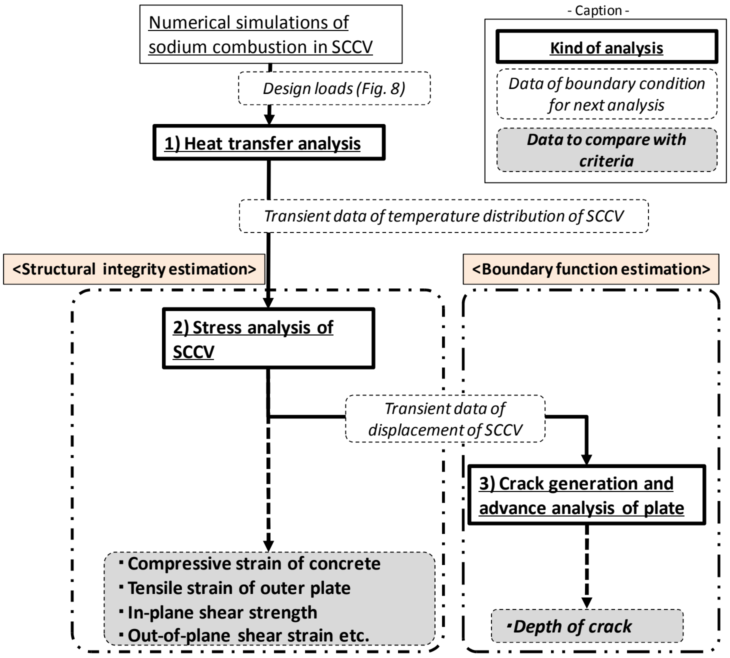


Fig.18 Outline of analysis of the SCCV behavior

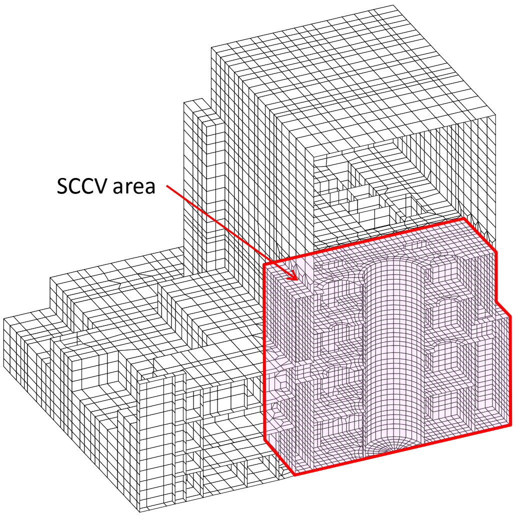


Fig.19 FEM model for the structural integrity analysis

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REFERENCES

[1] Ozaki, M., et al., 2001, “Study on Steel Plate Reinforced Concrete Bearing Wall for Nuclear Power Plants Part 1; Shear and Bending Loading Tests of SC Walls”, Proc. of 16th SMiRT, Paper #1554.
[2] Fujita, T., et al., 2005, “Development of Advanced Concept for Shortening Construction Period of ABWR Plant (Part 3)”, Proceedings of 13th ICONE, ICONE13-50646.
[3] Hosoya, T., et al., 2009, Proc. of ICAPP’09, “Conceptual Design for Japan Sodium-Cooled Fast Reactor(4): Developmental Study of Steel Plate Reinforced Concrete Containment Vessel for JSFR”, Paper 9418.
[4] Ikeda, M., et al., Proceedings of FR’91, “DESIGN AND CONSTRUCTION OF REACTOR CONTAINMENT SYSTEMS OF THE PRPTOTYPE FAST BREEDER REACTOR MONJU”, 8-7.
[5] Kubo, S., et al., Proceedings of Global 2005, “Status of Conceptual Safety Design Study of Japanese Sodium cooled Fast Reactor”, Paper No.221.
[6] U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002, Crosscutting Risk and Safety R&D Scope Report, GIF-011-00.
[7] JEA (Japan Electric Association), 2009, JEAC (Japan Electric Association Code) 4618-2009.