Performance-based Design of Stiffened Steel Plate Concrete Wall in Fire

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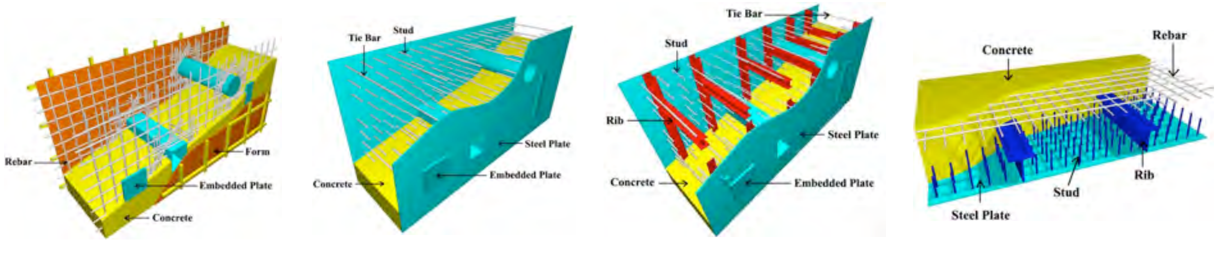
1 ABSTRACT

This paper describes proposed the design method based on the fire performance test results of stiffened steel plate concrete (SSC) wall with ribs. SSC wall is a composite structure consisting of surface steel plate with stud and rib instead of rebar of reinforced concrete wall. In fire conditions, the surface steel plate of SSC wall is directly exposed to fire attacks, therefore the load-carrying capacity of the wall is reduced due to the degradation of material property. Although the reduction of stiffness and strength is expected, a minimum fire resistance rating of three hours should be provided for the application of SSC wall in the nuclear power plant structure.

In this study, the testing of a loaded SSC wall under ISO 834(1999) fire conditions was carried out in generic transient state testing way and also a simple design method was proposed based on the fire performance test result to ensure required fire resistance rating. The design specifications are included in SC structure standard for the nuclear facilities in Korea.

2 INTRODUCTION

SC wall has good structural performance under normal and abnormal load conditions. Steel plates on both sides of concrete are appropriately connected by the tie bars or the angle trusses shown in Fig. 1. The tie bars in SC wall play a role as the member for preventing buckling of the surface steel plates and for out-of-plane shear strengthening, and the surface steel plates play an important role as not only the rebar for tension reinforcement but also the form for concrete placement. Therefore, SC structure does not need to have reinforcing bar that need to be assembled and disassembled. The surface steel plates are designed to withstand a lateral pressure from concrete placement and to maintain a minimum displacement under construction. As a result, it is possible to achieve the shortening of the construction period as well as the enhancing of the structural safety, and it is effective option for a main building construction in the nuclear power plant.



(a) RC wall (b) Unstiffened SC wall (c) Stiffened SC wall (d) Half SC slab

Figure 1. Steel Plate Concrete (SC) structures

The countries having the nuclear power plants are encouraging research and development sector to find ways to construct safer and economically more feasible nuclear power plant. Modularization using SC structure has been proposed as a solution to these efforts in Japan and the United States. Japan developed design specifications, JEAG 4618(2005) which is based on allowable stress design method, and modularization design using SC structure has applied for the United States nuclear power plants (Narendra et al., 2008).

Recently, various studies of structural modules using SC structure have been performed for shortening of construction period and enhancement of structural safety of APR1400 nuclear power plant structures in Korea. As a result of the research, the design code and the design technique based on the limit state design method have been developed, and SSC structure with stiffening ribs was incorporated in this code. Finally, an internal structure layout in a reactor containment building using SC structure has been developed.

SSC wall consists of two ribbed surface steel plates encasing concrete shown in Fig. 1. Internal structure using the ribs should be installed on the surface steel plate not only to prevent the displacement of un-stiffened steel plate concrete (USC) module during construction but also to improve the strength of that under commercial loads. According to experimental tests, SSC wall shows the improvement of compressive strength, tensile strength, flexural strength and out-of-plane shear strength compared to USC wall. However, SC structures including SSC wall and half steel plate concrete (HSC) slab etc. are relatively unfavorable comparing with reinforced concrete structure because the surface steel plate is directly exposed on fire.

According to standard review plan (SRP) section 9.5.1(1981), a fire barrier wall in the nuclear power plant structure shall be required to endure more than three hours under the fire conditions, and the fire test shall be performed in accordance with NFPA 251(1999) and ASTM E 119(2008). In a recent, international standard ISO 834 is broadly applied as the fire test method and it is possible to carry out according to this code because the fire heat curve of the code comprise that of ASTM E 119. Therefore, ISO 834 application for the fire test of the nuclear power plant structure is appropriate.

A few fire tests on SSC wall using transient steady state method were performed, and parametric studies were carried out by the authors. Our research focused on the relations between axial member force and fire enduring time of SSC wall, and we developed the fire design specifications for SC structure based on the fire test results. The fire test results and the fire performance design specifications are described in this paper.

3 FIRE TEST AND DESIGN REQUIREMENTS

3.1 Test Requirements

Fire barriers in the nuclear power plant buildings should provide over a minimum fire resistance rating of three hours in accordance with SRP 9.5.1(1981), and the fire test shall be performed according to NFPA 251 and ASTM E 119. It is assumed that a fire may occur at any time but is not postulated to occur simultaneously with the plant accidents or the most severe natural phenomena(REG Guide 1.189, 2007). Recently, ISO 834 is applied as the fire test method, and our test also was performed in accordance with the code. The fire heat curve of the code comprises that of ASTM E 119 shown in Fig. 2.

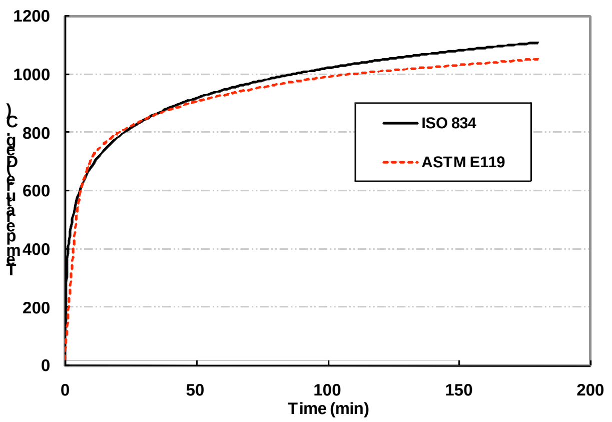


Figure 2. Fire heat curves

Combination of the heat load with a dead load and a live load that act during a fire is defined as follows.

$$(0.9 \text{ or } 1.2)D + T + 0.5L + 0.2S \tag{1}$$

Where, D is a dead load including the self-weight of the structures and fixed equipments etc., L is a live load including moving equipment and impact load, S is the snow load, and T is the heat load and the heat effect under the fire conditions. Alternatively, an actual axial force ratio of the fire barrier wall based on the design results can apply as axial load during the fire performance test. In case of safety-related structure in nuclear power plant, the ratio of axial design member force to maximum axial member force is less than 40 %.

3.2 Test Set-Up

In accordance with ISO 834 and a minimum thickness of safety-related structure, the test specimens of SSC wall is 3,000 × 3,000 mm in the plane dimension with a thickness of 300 mm shown in Fig. 3. Additionally, the test using a specimen with reduced width of 1,650 mm was performed for minimizing effects of axial load eccentricity show in Fig. 3. A fairly extensive set of thermal measurements were taken to measure through wall thickness temperature, and lateral displacements and strains were measured to investigate the structural response.

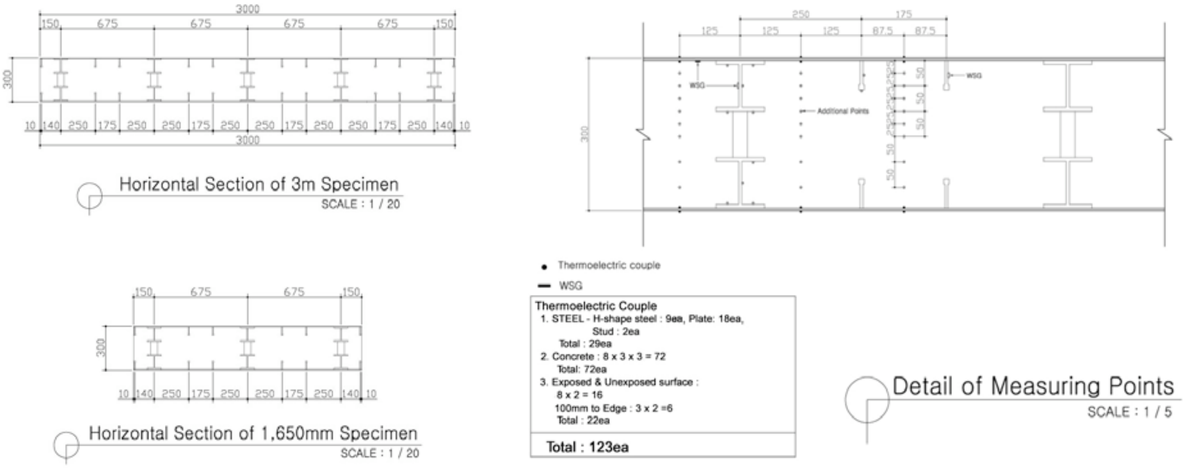
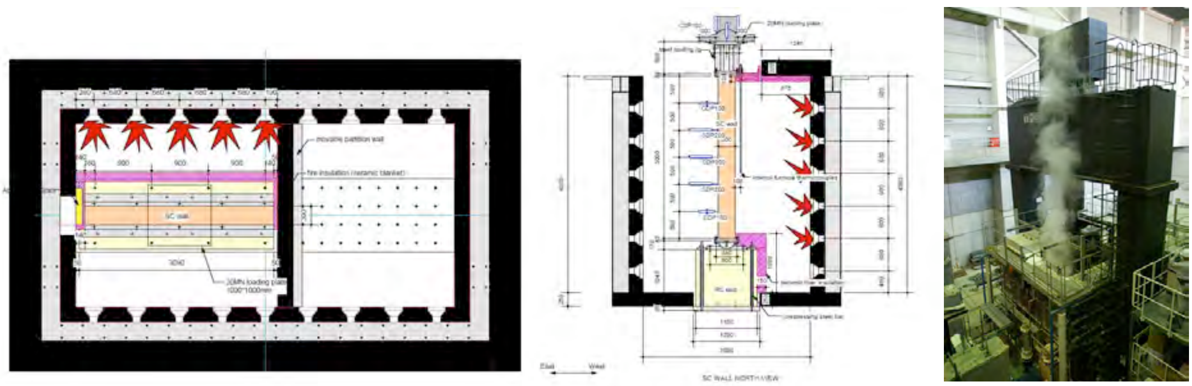


Figure 3. Test specimens

Testing of a loaded structure under the fire conditions were performed by transient state testing method. In transient state testing, axial load was applied to the structure first, and then the load was held constant and the structure was exposed to the fire attack shown in Fig. 4. The test was terminated when lateral displacement failure criteria was reached. The failure criteria, which is the loss of load-bearing capacity, is both amount and rate of the displacement as follows.

$$C = h/100 \text{ mm} \tag{2}$$

$$dC/dt = 3h/1,000 \text{ mm/min} \tag{3}$$



(a) Plan (b) Side (c) Test scene

Figure 4. Transient state test method

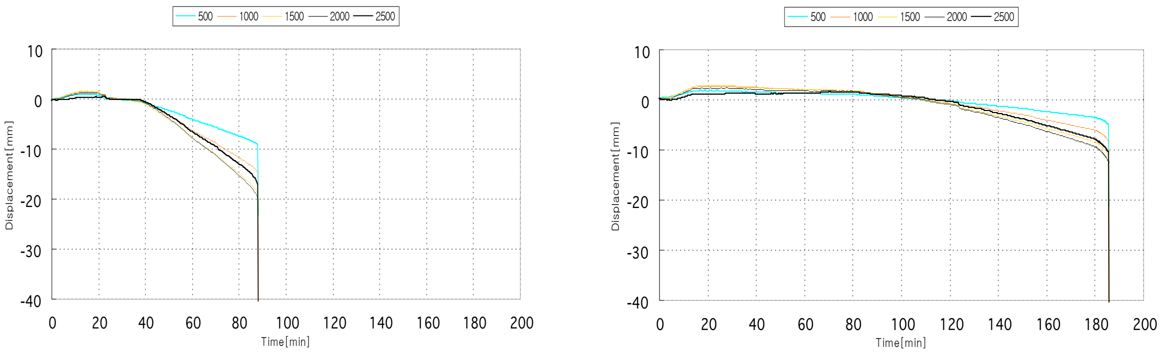
Under global buckling, an effective length of SSC wall is the most important parameter that should be accurately determined. The effective length is highly dependent on the boundary condition of the test specimen. As shown in Fig. 5, a rotational support is installed at the bottom of the wall, and a loading frame also is installed at the top of the wall. If the wall is perfectly loaded through its center and the wall is initially perfect. However, with imperfections in the wall due to large-sized dimension of the specimen, any slight tendency for the wall to rotate at the ends would affect the boundary conditions. Therefore, our test considered the test specimen with a reduced width for a final test.

(a) Loading frame (b) Rotational support

Figure 5. Boundary conditions for fire test

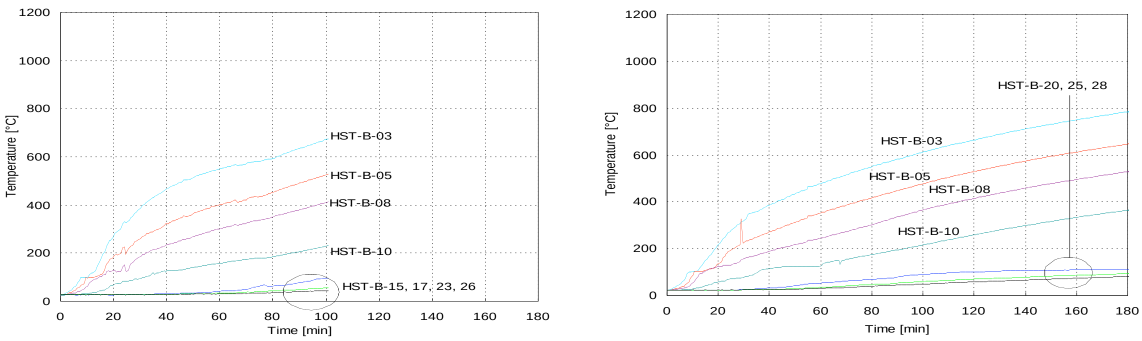
3.3 Test Results

According to our test results, the resistance rate is largely affected by the ratio of design axial strength (P_n) to axial load (N). In case of the ratio of 63 % the resistance rating is 89 minutes but in case of the ratio of 40 % the rating is over 180 minutes shown in Fig. 6. The loss of load-bearing capacity caused by the degradation of steel plate and concrete strength. Fig. 7 and Fig. 8 represent the temperature distributions through SSC wall thickness and Fig. 9 shows the calculated residual strength of concrete.



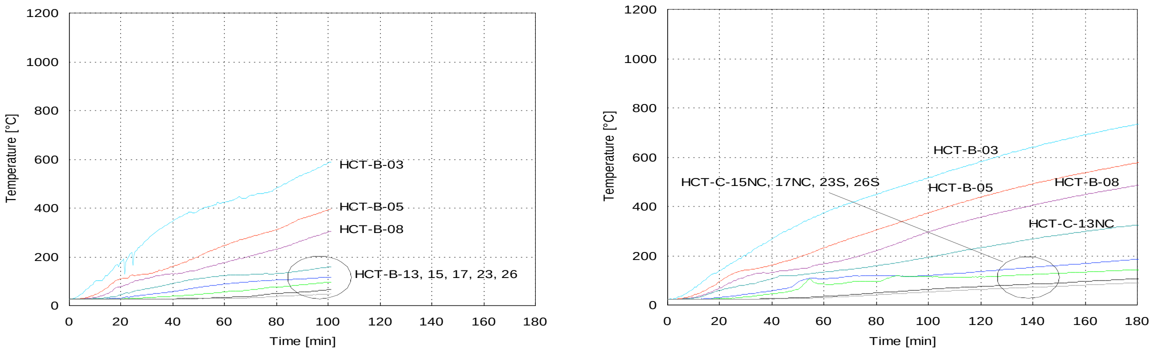
(a) Axial force ratio of 63 % (b) Axial force ratio of 40%

Figure 6. Load-bearing capacity according to axial force ratio



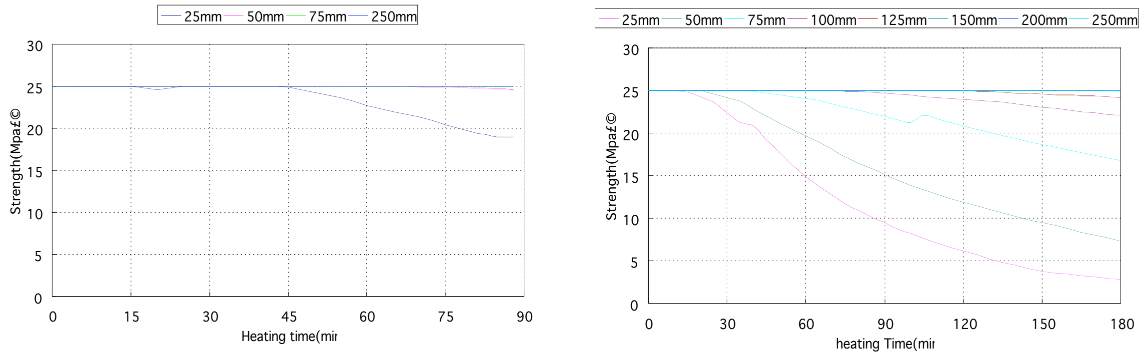
(a) Axial force ratio of 63 % (b) Axial force ratio of 40%

Figure 7. Temperature distribution of ribs according to the fire heating



(a) Axial force ratio of 63 % (b) Axial force ratio of 40%

Figure 8. Temperature distribution of concrete near ribs according to the fire heating



(a) Axial force ratio of 63 % (b) Axial force ratio of 40%

Figure 9. Residual strength of concrete according to the fire heating

As a result, lateral displacement to the fire-exposed surface occurs at initial fire heating, and then the displacement is suspended and the lateral displacement to the opposite side occurs simultaneously after 20 minutes. The bending moment due to a heat expansion of undamaged material occurs in SSC wall at initial fire heating. However, the strength degradation of the materials due to the temperature increase causes the stiffness reduction of fire-exposed surface, and then the direction of the lateral displacement is changed. As a result of the fire test, the recorded axial deformation-time relationship can be divided into four parts. A phase of steady increase due to the wall expansion is followed by a sharp contraction and then gradual contraction in the wall axial deformation, and the wall experiences another sharp contraction before failure. Before heating starts, the surface steel and the concrete share the applied load by composite action. During the initial stages of the fire test the surface steel plate expands faster than the concrete. The applied load is now mainly resisted by surface steel plate and the first phase corresponds to thermal expansion of the surface steel plate. As the surface steel plate temperature increases to a degradation stage of material strength, the surface steel plate loses its load-carrying capacity and the wall suddenly contracts due to buckling of surface steel plate. This affects the second stage behavior and is accomplished by local bulging of surface steel plate. Because concrete has sufficient load-carrying capacity, the axial load is shed from surface steel plate to concrete. The wall response is characterized by a gradual contraction until the axial load exceeds a combined resistance of surface steel plate and concrete at much higher temperature.

Fig. 10 shows the failure appearances after the fire test. Local bulging of surface steel plate and spalling of concrete with the failures of welding parts of studs and tie bars were found in cut section of SSC wall specimens. However, the fillet welding parts between surface steel plate and ribs and the groove welding parts between both surface steel plates do not detect the failure.

As the fire test results, the necessity of the vapor holes and the axial load ratio restriction was proposed and it was considered in the fire performance design specifications. Since load-carrying capacity depends on a residual strength of the concrete which resists mainly against the axial load, it is also considered in the specifications as a simple design method for SC wall.

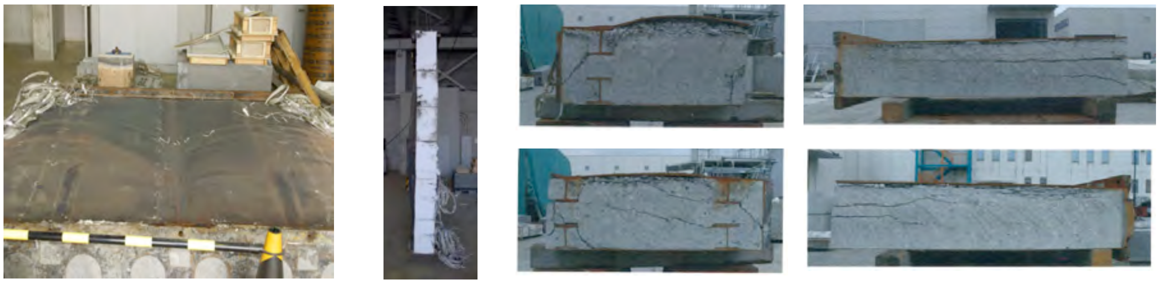


Figure 10. Typical failure appearances after fire test of SSC wall

4 ANALYSIS AND DESIGN SPECIFICATIONS

4.1 Effect of Axial Force Ratio

Axial force ratios of typical safety-related building in the nuclear power plant were investigated in this study shown in Table 1. Since the maximum axial load ratio is 20.14 % at the pressurizer shield wall in case of severe environment load combination and the maximum value is 13.26 % in case of normal load combination, the load-carrying capacity of SSC wall under fire will be maintained over three hours based on the fire test results and satisfied the requirements of SRP 9.5.1.

Table 1. Typical axial load ratio of reactor containment building

Member		Thick(in)	N/f_{ck}	P_n(Kip/ft)	N (Kip/ft)	N/ P_n
Secondary Shield Wall	(Dead + Live) load	48	4.98 %	-1830.8	-143.5	7.84 %
	Normal Load	48	5.14 %	-1830.8	-148.0	8.09 %
	Severe Environment Load	48	11.91 %	-1830.8	-342.9	18.73 %
IRWST	(Dead + Live) load	74	6.55 %	-2907.2	-290.7	10.00 %
	Normal Load	74	8.68 %	-2907.2	-385.5	13.26 %
	Severe Environment Load	74	12.38 %	-2907.2	-549.5	18.90 %
Steam Generator Shield Wall	(Dead + Live) load	60	1.18 %	-2325.8	-42.5	1.83 %
	Normal Load	60	1.81 %	-2325.8	-65.2	2.80 %
	Severe Environment Load	60	9.48 %	-2325.8	-341.4	14.68 %
Pressurizer Shield Wall	(Dead + Live) load	33	2.71 %	-1230.2	-53.7	4.36 %
	Normal Load	33	2.38 %	-1230.2	-47.1	3.83 %
	Severe Environment Load	33	12.51 %	-1230.2	-247.8	20.14 %

Kodaria et al. (2003) proposed an empirical equation for the fire performance of SC wall that consists of the relations of axial load (N), wall height (H) and wall thickness (T). The tests were carried out on the cases of H/T ratio of 9 and 15, and then they proposed equations (4) and (5). Where, σ_b is the compressive strength of concrete under normal temperature and A_c is the section area of concrete.

$$\text{In case of H/T = 9; } \frac{N}{A_c\sigma_b} = 2.21 \times \left(\frac{1}{t}\right)^{0.323} \tag{4}$$

$$\text{In case of H/T = 15; } \frac{N}{A_c\sigma_b} = 2.30 \times \left(\frac{1}{t}\right)^{0.378} \tag{5}$$

Since the H/T ratio of our tests is 10, it can appropriately modify the equation as the relations between both equations (4) and (5). Fig. 11 represents the relationship of the axial force ratio and the fire load-carrying capacity. In case of H/T=10, the fire load-carrying capacity is 180 minutes at the axial force ratio of 40 % and 52 minutes at the axial force ratio of 60 %.

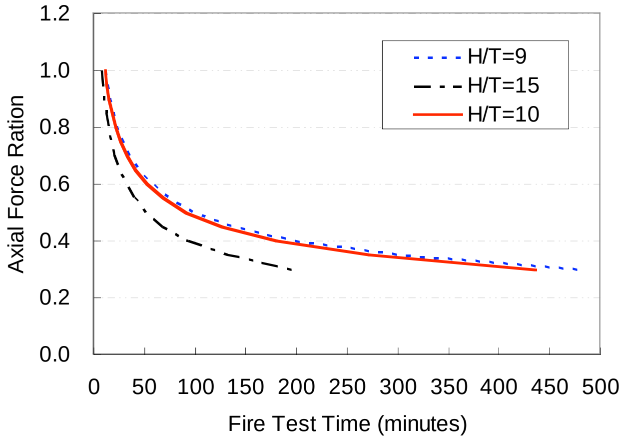
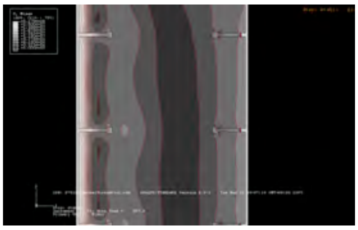


Figure 11. Relationships between axial force ratio and fire test time

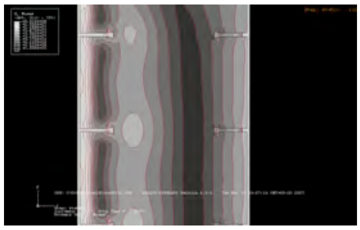
4.2 Assessment of Test Results

In test case of the axial force ratio of 63 %, heat transfer and heat stress analyses are performed using two-dimensional finite element method shown in Fig. 12. According to the analyses results, the maximum heat stresses are developed on the fire-exposed surface after 5 minutes, and then the maximum heat stresses move gradually to the fire-unexposed surface direction. At 30 minutes, the maximum stress is larger than the concrete strength near the depth of 30 mm, and the depth moves near 80 mm at 89 minutes.

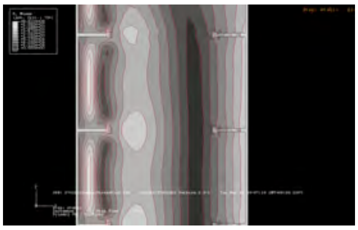
(a) 5 minutes



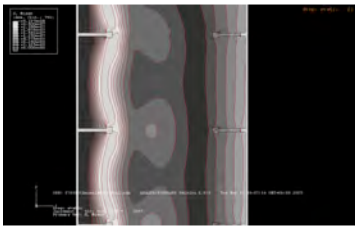
(b) 10 minutes



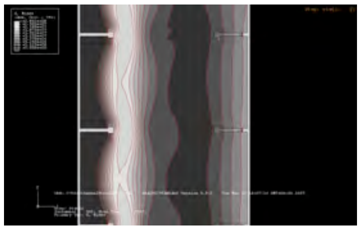
(c) 20 minutes



(d) 30 minutes



(e) 60 minutes

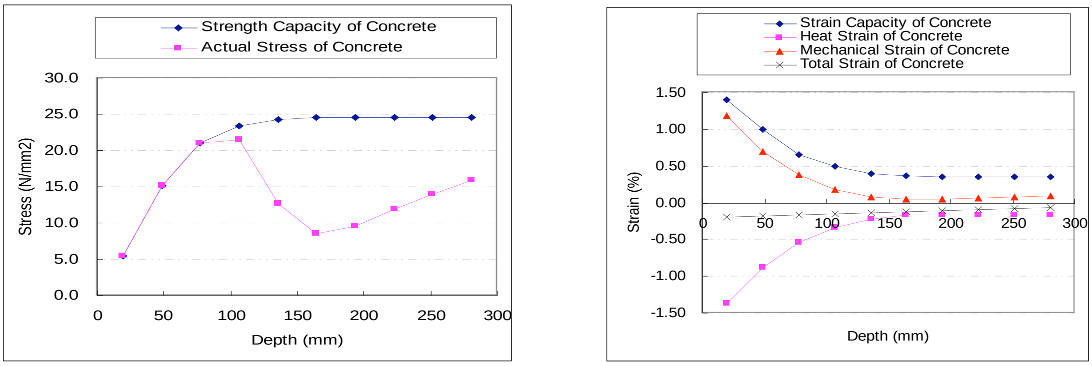


(f) 89 minutes

Figure 12. Stress contours of SSC wall resulting from heat transfer and heat stress analyses

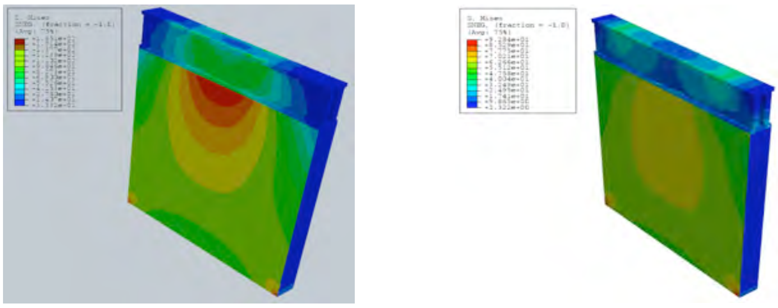
Fig. 13 represents the plot of a segmental analysis result using the temperature distribution data through SSC wall thickness during three-hour fire test. In case of the axial force ratio of 63 %, the actual stresses and the total strains are much less than the strength and the strain capacity. Therefore, the load-bearing capacity of SSC wall is theoretically maintained for three hours. Other items such as an explosive vapor pressure against the surface steel plate and a boundary condition of the test etc. can affect the load-bearing capacity, and therefore those effects should be considered in design specifications.

Fig. 14 shows the stress contour in SSC wall test specimens according to a decrease of the axial force ratio and an increase of the loading frame stiffness. Stresses in the surface steel plate are approximate 90 % of the buckling strength capacity for the axial force ratio of 63% and are approximate 39 % of the buckling strength capacity for the ratio of 40 %. Fig. 15 represents the analysis results considering the heat distributions through the wall thickness and both axial force ratios during 89 minutes. According to the analysis results the initial stress due to a decrease of the axial load is definitely reduced, but a change of the stress under both temperature and the axial load is ambiguous the same as the segmental analysis results.



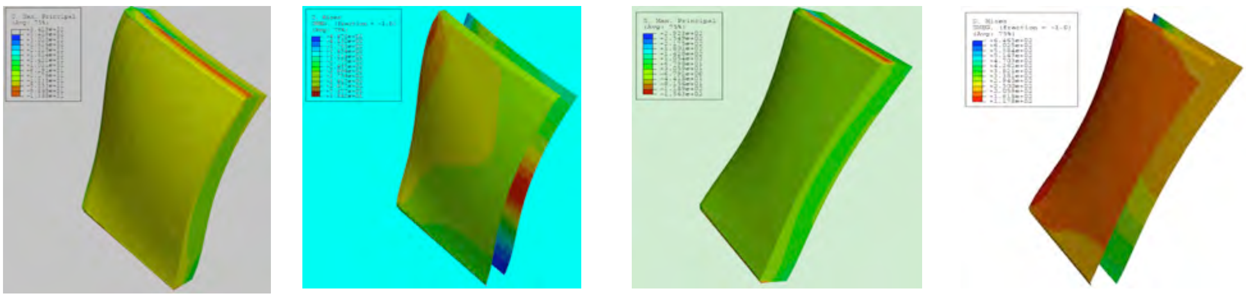
(a) Stresses (b) Strains

Figure 13. Segmental analysis results



(a) Axial force ratio of 63% (b) Axial force ratio of 40%

Figure 14. Stress contours of test specimens under axial load only



(a) Axial force ratio of 63% (b) Axial force ratio of 40%

Figure 15. Stress contours of concrete and steel plate under both temperature and axial loads

4.3 Design Specifications

SC wall design specifications for the fire condition consists of the design requirements for fire conditions, mechanical properties of steel and concrete at high temperature, temperature distribution at cross-section, finite element method (or fiber model analysis), segment analysis, simple design method, and required detail.

Based on the fire test results and the theoretical studies the specifications are developed for SC wall design under fire condition. In this specifications, SC wall with the thickness (t) of above 300 mm and the ratio of below H/t=13 shall be considered the fire barrier structures satisfying license requirements if the axial force ratio is less than 40 %. There are three design methods for the fire barrier design of SC wall such as the fire model analysis, the segment analysis, and the simple design method. The simple design method is the safe design method. Moreover, the simple design method is adapted because structural components in the nuclear power plant are typically thick enough to satisfy a three-hour fire resistance requirement even without a precise design method (Korea Electric Association, 2008). In proposed simple design method for SC wall, a damaged depth for the stiffness calculation is assumed as 100 mm based on the test data of Kodaira et al. using SC wall with a thickness of 200 mm and the test result of the authors using SSC wall with a thickness of 300 mm. A damaged depth for the strength calculation is assumed as 50 mm based on the same test results.

5 CONCLUSION

1) Fire tests of large-sized SSC wall are performed by transient state test method, and authors make clear that load-bearing capacity of the wall mainly depends on the magnitude of axial load and the effects of an explosive vapor pressure. Therefore, the axial force ratio shall be limited as less than 40 % and the vapor holes should be installed on surface steel plate.
2) Based on the temperature distribution through SSC wall thickness due to fire test and the degradation rate of material properties due to existing equations, simple design method and segmental analysis method are proposed in the design specifications developing authors.
3) Most of fire barrier walls in safety-related buildings of nuclear power plant can satisfy the license requirements for fire design because author’s tests comprise the minimum wall size of structures and the axial force ratio of structures. If axial force ratio is over 40 %, a fire design should be performed using proposed design method.

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