Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division V

RESISTANCE OF SC WALLS SUBJECTED TO MISSILE IMPACT: PART 2. MIDDLE-SCALE TESTS

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ABSTRACT

According to the International regulations for nuclear power plants, a nuclear power plant must be able to withstand local impact loads, such as aircraft engine impact, and internal and external missile impact. Although extensive studies on the local impact behavior of the conventional RC (reinforced concrete) wall have been performed, and the design methodologies to prevent local failure are already established, there is no such design methodology available for SC (steel-plate concrete) walls except for the one recently suggested by J.C. Bruhl et al. (Bruhl, J. C., 2015).

In this study, we performed a series of studies on the impact resistance of SC walls to evaluate the local impact behaviour of the SC walls subjected to missile impact: preliminary analytical study, middle-scale impact tests, and small-scale impact tests. This paper is about part2 middle-scale impact tests.

A total of 15 middle-scale impact tests were planned to investigate the impact resistance performance of SC walls at the extreme performance testing center of Seoul National University in Korea. The specimens were designed with various test parameters including wall thickness, reinforcement ratio, yield strength of steel plate, and tie-bars. Initial and residual velocity of the missile, strain and acceleration of the back plate, local failure mode and deformation size, etc. were measured using high speed cameras and various instrumentation devices. The results from this study will be used to improve and optimize the AISC N690 design equation for SC walls subjected to missile impact.

INTRODUCTION

International and Korean regulations for nuclear power plants strictly prescribe the design requirements for local impact loads, such as aircraft engine impact, and internal and external missile impact.
These days, SC structure is widely used internationally for nuclear power plant design because of its efficiency of fabrication, erection, and construction. Although extensive studies on the local impact behavior of the conventional RC (reinforced concrete) wall have been performed, and the design methodologies to prevent local failure are already established and included in NEI 07-13 (NEI, 2011) and DOE-STD-3014 (DOE, 2006), there is a lack of technology for evaluating the local impact behavior as well as the design methodology for steel-concrete (SC) structures.

Recently Bruhl et al. proposed a three step design method which can be applied to the design of SC walls to resist perforation from missile impacts (Bruhl, J. C., 2015). However, according to our previous study (Kim, K. S., 2017), the accuracy of the design method of SC walls to prevent perforation from missile impact can be improved.

In this study, a series of studies on the impact resistance of SC walls to evaluate the local impact behaviour of the SC walls subjected to missile impact were performed: preliminary analytical study, middle-scale impact tests, and small-scale impact tests. This paper is about part2 middle-scale impact tests.
Up to the present time, six of fifteen middle-scale impact tests have been performed to investigate the impact resistance performance of SC walls and develop optimum design equation.

TEST PLAN

Specimen Design

In order to determine the design parameters for test specimen, a lot of preliminary analyses are carried out using commercial FE program LS-DYNA. Finally the following main parameters were considered in the specimen design and Table 1 shows final specimen design: wall thickness, reinforcement ratio, strength of plate, tie bar, and structural type. Total eight sets of middle scale test specimens which consist of the internal concrete, steel surface plate, studs, and tie bars are considered. The detailed designs of the typical test specimen are shown in Figure 1. The overall size of the test specimens is 2,100 mm x 2,100mm, and the wall thickness are various from 240mm to 480mm, and the surface plate thickness are 6mm and 9mm.

Table 1. Specimen Design

No	Specimen Name	T_{SC} (mm)	T_P (mm)	F_y (MPa)	Tie bar	W (kgf)	$V_{P\text{-}AISC}$ (m/s)	Expected Behavior	Note
1	SC-T320-3.7	320	6	355	X	60	122	Perf./Stop	2EA
2	SC-T320-3.7-tie	320	6	355	O	60	122	Perf./Stop	2EA
3	SC-T480-3.7	480	9	355	X	80	160	Perf./Stop	2EA
4	SC-T240-5.0	240	6	355	X	40	130	Perf./Stop	2EA
5	SC-T360-5.0	360	9	355	X	60	159	Perf./Stop	2EA
6	SC-T360-5.0-tie	360	9	355	O	60	159	Perf.	1EA
7	SC-T360-5.0-HSA	360	9	460	X	80	147	Perf./Stop	2EA
8	RC-T320-3.7	320	Rebar	-	X	60	113/78	Perf./Stop	2EA

[Note] Con′c strength: 35MPa, T_{SC}: wall thickness, T_P: plate thickness, F_y: yield stress of steel plate
W: missile weight, $V_{P\text{-}AISC}$: perforation velocity by AISC design equation (Bruhl, J. C., 2015)

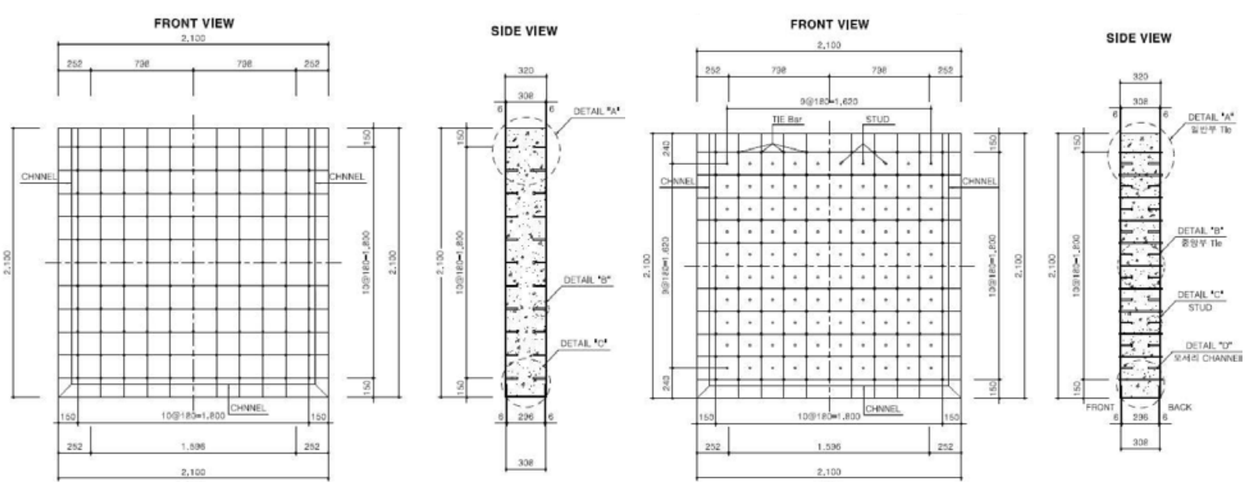


Figure 1. Configuration of the Typical Test Specimen

Two tests were carried out for each test sets to find critical perforation velocity except for the specimen of SC-T360-5.0-tie: one for perforation behavior and the other one for stop. The projectile weight and speed were determined considering required critical failure modes based on the results of preliminary analysis. The projectile diameter is 150mm with an overall length of 280mm, 430mm, and 580mm. The projectile weights are 40kgf, 60kgf, and 80kgf, and the front end of the projectile have a blunt shape.

Test Facility and Instrumentation

All middle-scale impact tests were conducted using the gas-gun at the extreme performance testing center of Seoul National University in Korea. The internal diameter of gun tube is 250mm and the total length is about 20m. The maximum launching velocity of the gas-gun is about 220m/s for 100kgf projectile.

Figure 2 shows the impact test facility and the overall view of the instrumentation setup. Six Strain gauges, two accelerometers, and four displacement censors were applied to the back of all SC panel targets before testing starts. An optical laser measuring device was installed to measure the projectile velocity in front of the SC panel and two high speed cameras were used to record the penetrator both before and after entering the SC target.

(a) test facility (b) instrumentation setup

Figure 2. Test Facility and Instrumentation

IMPACT TEST RESULTS

SC-T360-5.0-HSA-1st

The impact test for SC-T360-5.0-HSA is the test for the SC panel which has SC wall thickness of 360 mm and steel plate thickness of 9 mm. The reinforcement ratio is 5% and the yield strength of steel plate is 460MPa (High strength steel). The missile weight is 80kgf and the intended missile speed is 165 m/sec. The anticipated failure mode based on the result of preliminary analysis is perforation.

Figure 3 shows the actual impact test results of SC-T360-5.0-HSA-1st. The measured impact velocity of the projectile was 168 m/s and the failure mode was perforation just like the expectation. The steel plate of the front side was clearly cut and the back plate was also torn completely as shown in Figure 3. The perforated location of the back plate was somewhat off from the center of the panel. Most of the studs near the impact area were failed and the concrete of the impact area was crushed completely. The measured residual velocity of the projectile after perforation was about 45 m/s.

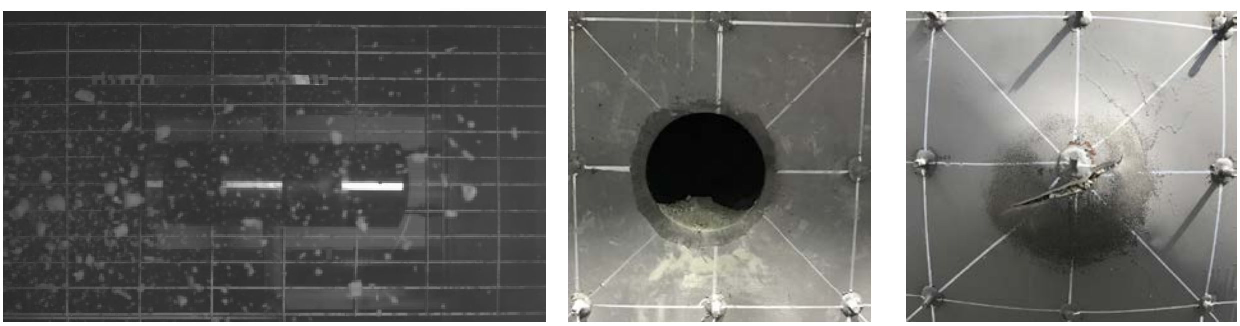
(a) projectile impact (b) front steel plate (c) back steel plate

Figure 3. Test Results (SC-T360-5.0-HSA-1st)

SC-T320-3.7-tie-1st

The impact test for SC-T320-3.7-tie-1st is the test for the SC panel which has SC wall thickness of 320 mm and steel plate thickness of 6 mm. Especially, tie-bar was installed for this specimen as well as stud. The reinforcement ratio is 3.7% and the yield strength of steel plate is 355MPa (Normal strength steel). The missile weight is 60kgf and the planned missile speed is 165 m/sec. The expected failure mode based on the result of preliminary analysis is bulging and stop.

Figure 4 shows the local impact behavior of the SC-T320-3.7-tie-1st from the actual test results. As was expected, the failure mode of the SC panel was bulging and the measured impact velocity of the projectile was 165 m/s. The steel plate of the front side was clearly cut out. The back plate was slightly torn out but there was no perforation as shown in Figure 4. From this result, we can see that the critical perforation velocity of this SC panel is slightly bigger than 165m/s.



(a) projectile impact (b) front steel plate (c) back steel plate

Figure 4. Test Results (SC-T320-3.7-tie-1st)

Table 2. Summary of Test Results

No	Specimen Name	T_{SC} (mm)	T_P (mm)	Tie bar	W (kgf)	$V_{P\text{-}AISC}$ (m/s)	V_{TEST} (m/s)	Test Results
1	SC-T320-3.7-1st	320	6	X	60	122	165	Stopped
2	SC-T320-3.7-tie-1st	320	6	O	60	122	165	Stopped
4	SC-T240-5.0-1st	240	6	X	40	130	203	Perforated
5	SC-T360-5.0-1st	360	9	X	60	159	180	Stopped
6	SC-T360-5.0-tie-1st	360	9	O	60	159	179	Stopped
7	SC-T360-5.0-HSA-1st	360	9	X	80	147	168	Perforated

Table 2 shows the summary of test results. From these test results, we can confirm the actual local impact behavior of SC walls subjected to missile impact load.

The test results, which were carried out in this study, are compared with the calculation results using the three step design method for SC walls recently proposed by Bruhl et al. The test results show the similar failure trends with calculations. However, as in our previous study (Kim, K. S., 2017), the proposed design method was considered to be somewhat conservative. That is, the critical perforation velocity of the test specimen calculated using the design equation were so lower than the critical perforation velocity from test results generally as shown in Table 2.

But, for the high strength steel, three step method was not so conservative due to the low strain-rate effect. The effect of tie bar was not significant as shown in Table 2(No.1 vs No.2, No.5 vs No.6).

CONCLUSIONS

The conclusions of this study drawn from these middle-scale impact tests performed until now are given below.

From the series of middle-scale impact tests, the actual local impact behaviors of SC walls subjected to missile impact load have been characterized.
Although the test results show the similar failure trends with calculation results, generally, the proposed three step design method was conservative as expected.
The effect of tie bar was not significant for the local impact behavior of SC walls.

Finally, once all the experiments are over, the results from this study will be used to improve the AISC N690 design equation for SC walls subjected to missile impact.

ACKNOWLEGEMENTS

The research presented in this paper was funded by Korea Hydro and Nuclear Power Co., LTD (KHNP).

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