Performance Evaluation of an Aboveground LNG Storage Tank Cover using Nondestructive and Destructive Tests

Sungnam Hong, Sun-Kyu Park, Jieun Jeong, and Jinwoong Choi

Abstract—In this study, a new procedure for inspecting damages on LNG storage tanks was proposed with the use of structural diagnostic techniques: i.e., nondestructive inspection techniques such as macrography, the hammer sounding test, the Schmidt hammer test, and the ultrasonic pulse velocity test, and destructive inspection techniques such as the compressive strength test, the chloride penetration test, and the carbonation test. From the analysis of all the test results, it was concluded that the LNG storage tank cover was in good condition. Such results were also compared with the Korean concrete standard specifications and design values. In addition, the remaining life of the LNG storage tank was estimated by using existing models. Based on the results, an LNG storage tank cover performance evaluation procedure was suggested.

Keywords—Destructive test; LNG storage tank; Nondestructive test; Performance evaluation procedure; Remaining life.

I. INTRODUCTION

LIQUEFIED Natural Gas (LNG) is an environment-friendly natural gas from which impurities such as water and sulfate had been removed. With the increasing preference for environment-friendly fuels, demand for LNG has steadily increased. The LNG storage tanks in Korea were built in the late 1980s, when natural gas was imported and distributed, and the tanks are now deteriorating. Some countries have their own evaluation criteria for the remaining life of LNG storage tanks and for extending their availability period, but Korea does not have such evaluation criteria, due to its concept of re-testing [1].

There are three types of LNG storage tanks, according to the relative height of the ground to the tank: aboveground, inground, and underground. An LNG storage tank has a double-layer structure, similar to that of a giant thermos bottle. Its outer cover is a post-tension concrete wall that sustains all loads. Its inner cover is composed of membrane walls that are sealed with stainless steel to prevent liquefied and gaseous

Sungnam Hong (Ph.D, Research Professor) is with the Department of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea, (phone : 82-31-290-7530; fax : 82-31-290-7949; e-mail : cama77@skku.edu).

Sun-Kyu Park (Ph.D, Professor) is with the Department of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea, (e-mail : skpark@skku.edu).

Jieun Jeong (B.S, M.E. Student) is with the Department of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea, (e-mail teff433@naver.com).

Jinwoong Choi (M.E, Ph.D Student) is with the Department of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea, (**Corresponding author**, phone : 82-31-290-7530; fax : 82-31-290-7949; e-mail : cjw85@skku.edu).

LNG from leaking [2]. For this kind of structure, performance evaluation techniques such as nondestructive tests that do not affect the structure are desirable. Studies on nondestructive tests for LNG storage tanks include the "Quality Test on the Inground Walls of LNG Storage Tanks" [2] and the "Nondestructive Test on the Electro-fusion Joints of PE Pipes in LNG Storage Tanks" [3]. In this study, the deterioration and performance of the concrete covers of aboveground LNG storage tanks that have been comparatively less researched, and an evaluation procedure, are suggested.

To begin with, cracks, peeling regions, exfoliation, and efflorescence were inspected with the naked eye, after which nondestructive test techniques such as the hammer sounding test, the Schmidt hammer test, and the ultrasonic test were used to estimate the concrete strength and to analyze the relative soundness of members. The data obtained from each nondestructive test were plotted on a contour graph, and the results of the three nondestructive tests were combined to understand the cover better [4]. Based on the data from the nondestructive tests, the sites of the destructive tests were designated before the compressive strength test, the chloride penetration test, and the carbonation test were conducted.

Fig. 1 Pilot LNG storage tank (1,000m^4)

II. TEST PROCEDURE

A. Overview of the Tests

The object of the tests was the 1,000m^3 pilot LNG storage tank located in the Incheon LNG receiving terminal, as shown in Fig. 1 As mentioned, few precedent studies on tests of the concrete cover of LNG storage tanks have been reported. In this study, a concrete cover test procedure is suggested using nondestructive tests and destructive tests [8]-[14], as described in Fig. 2. The suggested procedure can be used for regular performance evaluation of the concrete cover of LNG storage tanks. Before the nondestructive tests were conducted, the LNG storage tank was sectionalized into a front side, a back side, a right column, and a left column. The front and back sides were gridded with a horizontal distance of 27 cm and a vertical distance of 54 cm, as shown in Fig. 3. Numbers were given clockwise at each horizontal intersection, and letters were given in alphabetical order at each vertical intersection from the bottom to the top.
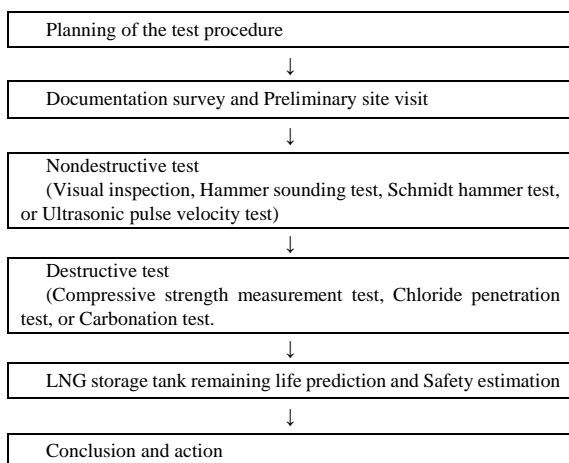

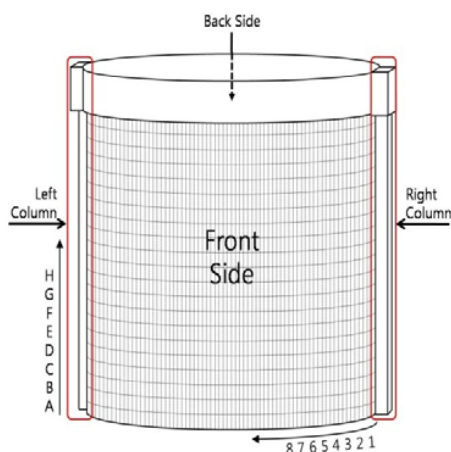Fig. 2 LNG storage tank performance evaluation procedure

Fig. 3 Grid system for the front and back sides of the LNG storage tank cover

B. Nondestructive Test

1) Visual Inspection

Visual inspection is a method of observing a structure using the naked eye or a simple apparatus. It may have a bias because the naked eye test is influenced by subjective judgments, so the reliability of visual inspection may be low. Since most problematic structures have anomalies on their surfaces, however, it is important for experienced engineers to notice the anomalies, understand the situation of the structure, and determine necessary measures. Through the visual inspection, the presence of cracks, peeling regions, exfoliation, and efflorescence was checked with the naked eye, and abnormal areas were recorded on photographs.

2) Hammer Sounding Test

The hammer sounding test is a technique for determining the internal conditions of structures by interpreting the hammer sounds generated when concrete surfaces are struck. The striker can subjectively interpret the hammer sounds, or the hammer sounds and striking forces are interpreted using computers. In this study, the former method was used for convenience. The results of this method may be decided on through subjective judgment, but their credibility is generally high. In the case of sound concrete without an internal anomaly, the hammer sounds are somewhat full; whereas in the case of problematic concrete with pores, deterioration, or cracks inside, the hammer sounds are somewhat empty. Areas that were found to have been normal were marked with 0, and areas with anomalies were marked with 1.

3) Schmidt Hammer Test

The most common destructive compressive strength test, the Schmidt hammer test, was used in this study. When a concrete surface is struck with a Schmidt hammer, various levels of restitution appear according to the concrete soundness. Using the correlation between the level of restitution and the concrete compression strength, the concrete compression strength can be estimated. Since the test result is not very reliable, however, this method was not used as the only index in this study, but other experiments to estimate the comparative strength inside the structure were also conducted. NR-type Schmidt hammers for regular concrete, which have 10-70MPa strengths, were used. The center point of each grid was struck five times, and the mean of the remaining three values was obtained after excluding the highest and lowest values [11], [12].

4) Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test takes advantage of the ultrasound property, the velocity in solid materials of which is decided on based on the density and elasticity of the material. Information and problematic sites inside concrete, such as its dynamic properties, cracks, and strength, can be estimated by measuring the ultrasonic pulse velocity at a certain distance [12], [13]. An ultrasonic test was conducted on the cracks and suspected surface areas of the LNG storage tank cover, which were discovered through visual inspection and the Schmidt hammer test. Considering the characteristics of the structure,

the oscillator and the receiver were placed on the same plane. Table I shows the relationship between the concrete quality and the ultrasonic velocity [4], [5].

TABLE I
CONCRETE QUALITY AND VELOCITY (RYALL, 2001).

Marked Level	Ultrasonic Velocity (km/sec)	Concrete Quality
1	> 4.5	Excellent
2	3.5-4.5	Good
3	3.0-3.5	Doubtful
4	2.0-3.0	Poor
5	< 2.0	Very poor

5) Combination of Nondestructive Tests

To make the evaluation of the comprehensive performance of the LNG storage tank cover convenient, the results of the nondestructive tests were combined. In the areas where the ultrasonic test was conducted, the combination of the hammer sounding test, the Schmidt hammer test, and the straight-line ultrasonic tests was conducted. Each of the tests was assumed to contribute 1/3 of the combined values. The data from each experiment item were converted into percentages of the maximum value of each experiment item. The areas where no ultrasonic test was conducted were assumed to have been sound, and their values were set at 1. The final results were supposed to have ranged from 0 to 100. The equation that was used for the calculation is as follows:

$$CE = (\frac{1}{3} \cdot \frac{HS(x)}{HS_{max}}) + \frac{1}{3} \cdot \frac{SH(x)}{SH_{max}} + \frac{1}{3} \cdot \frac{UPV(x)}{UPV_{max}} \times 100 \qquad (1)$$

In the preceding equation, CE represents the combined effect, and its value is between 0 and 100. HS_{max} represents the Hammer sounding test value; $HS(x)$, the Hammer sounding test value at each site; SH_{max}, the maximum Schmidt hammer value; $SH(x)$, the Schmidt hammer value at each site; UPV_{max}, the maximum straight-line ultrasonic velocity; and $UPV(x)$, the straight-line ultrasonic velocity.

C. Destructive Test

Based on the nondestructive test results, areas on the concrete cover that did not affect the structural durability were selected to obtain three concrete cores. Each of the cores had a diameter of 100 mm and a height of 200 mm.

1) Compressive Strength

The compressive strength test was conducted on the three concrete cores based on KS F 2405-10, and the mean value of the three cores was compared with the design strength of the cover concrete of the LNG storage tank [14].

2) Chloride Penetration Test

Permeation of chloride ions leads to corrosion of steel in concrete and development of cracks, peeling regions, and exfoliation. In addition, corrosion reduces the sectional area of steel bars and adversely affects the durability of the structure [11]. Considering the seaside location of LNG storage tanks, a test of their chloride content was conducted because chloride-induced corrosion was suspected. In this study, core samples were powdered before their chloride content was measured. The test was conducted based on KS F 2713-07.

3) Carbonation Test

Hardened concrete has a property of strong alkalinity (pH: 12.5-13) due to calcium hydroxide, which is a concrete hydrate. With the passage of time, the calcium hydroxide on the surface of concrete reacts with carbon dioxide in the air to change to calcium carbonate, and consequently, the concrete gradually loses alkalinity from the surface to a deeper area. As the neutralization process proceeds, the passive film on the surface of the steel in the concrete is destroyed, and the steel eventually erodes due to water, oxygen, or salt. This erosion reduces the concrete durability as chloride-induced corrosion does, and the lifetime of the structure is adversely affected [8]-[12]. Based on KS F 2596-04, a phenolphtalein method was used on the exposed area of the core in this study.

III. NONDESTRUCTIVE TEST RESULTS

It is not appropriate to immediately decide to repair, reinforce, or maintain the subject structure based only on the nondestructive test results in this study. The nondestructive test results, however, can be the bases of the selection of the destructive test sites and of the comprehensive determination of the structure durability, in combination with the destructive test results. In this study, the nondestructive tests were conducted as follows.

(1) Through visual inspection, the presence of cracks, peeling regions, exfoliation, and efflorescence on the subject structure was checked and photographed.

(2) The hammer sounding and Schmidt hammer tests were performed on the whole structure, and the results were recorded.

(3) Based on the results of Equations (1) and (2), a localized ultrasonic test was conducted in the suspected areas.

(4) Based on all the nondestructive test results, destructive tests were conducted.

A. Visual Inspection Results

During the visual inspection of the LNG storage tank cover, cracks similar to those shown in Fig. 4 (a) were observed, but they were not considered problems based on their widths and patterns. The cracks observed in sectors A117-C117 and B65 were also thought to have not affected the structure; but considering their lengths, an ultrasonic test was conducted. Other than the cracks and areas with peeling, exfoliation, or steel exposure, no serious anomaly that can result in structural problems was observed during the visual inspection of the LNG storage tank cover.

(a) Sector J86

(b) Sector A117-C117

(c) Sector B 65

Fig. 4 Cracks on the concrete wall

B. Hammer Sounding Test Results

With the presence of anomalies such as pores, deterioration, or cracks inside the structure, "empty" sounds were heard during the Hammer sounding test. The test results showed no abnormal area in all the sections. In addition, no damage such as exfoliation of the concrete cover occurred during the test.

C. Schmidt Hammer Test Results

Using the Schmidt hammer test results and the following suggested equations, the compressive strength of the concrete cover was estimated.

Materials Research Society of Japan

$$F_c = 13R_0 - 184 \tag{2}$$

Japan Testing Center for Construction Materials

$$F_c = 10R_0 - 110 \tag{3}$$

Architectural Institute of Japan

$$F_c = 7.3R_0 - 100 \tag{4}$$

In the preceding equations, F_c represents the estimated compressive strength, and R_0, the corrected result of the Schmidt hammer test[6]. Equation (1) showed overestimated results with large deviations, compared with the other suggested equations. In contrast, Equation (2) tended to be underestimated with a smaller deviation, compared with Equation (1). Equation (3) showed a compressive strength between that from the two equations with the smallest deviation, from among the three equations. The final concrete compression strength was calculated from the three equations. Fig. 5 shows a contour graph of the results. The estimated concrete strength had a mean of 41.55MPa and ranged from 31.64MPa to 48.80MPa. The estimated compressive strength exceeded the design strength of 30.00MPa, which is the standard for LNG storage tanks. Based on the results of the Schmidt hammer test, the strength of the structure was considered normal.
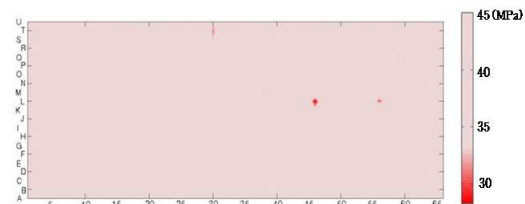
(a) Front
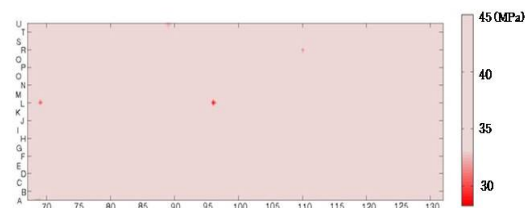
(b) Back

Fig. 5 Schmidt hammer test results

D. Ultrasonic Test Results

The ultrasonic test was conducted in the suspected areas based on visual inspection and the Schmidt hammer test. The test was conducted at the A117-C117 and B65 grids that had long cracks and at J46-M46, K56-N56, K68-N68, J97-M97, and Q110-T110, which were suspected based on the Schmidt

hammer test. The results of the ultrasonic test were measured as the velocity, and then compared with the results of the study of Ryall, which are presented in Table I [5]. Table II shows the comparison results. Based on the results of the ultrasonic test, the suspected areas in the previous nondestructive tests were deemed normal.

TABLE II
RESULTING ULTRASONIC VELOCITIES IN THE UNHEALTHY SECTORS

Sector	Average Ultrasonic Velocity (km/sec)	Concrete Quality
A117-C117	4.15	Good
B65	4.19	Good
J46-M46	4.28	Good
K56-N56	4.27	Good
K68-N68	4.01	Good
J97-M97	4.49	Excellent
Q110-T110	4.38	Good

E. Combined Results of the Nondestructive Tests

The results of the Hammer sounding test, the Schmidt hammer test, and the straight-line ultrasonic tests were combined using Equation (1), and then plotted on a contour graph. The converted marks of the concrete cover of the LNG storage tank, which were calculated using a combination of nondestructive tests, ranged from 88.13 to 100, with a mean of 95.77, which confirmed that they were normal in all the sections. Fig. 6 shows the contour graph of the results of the combined nondestructive tests.
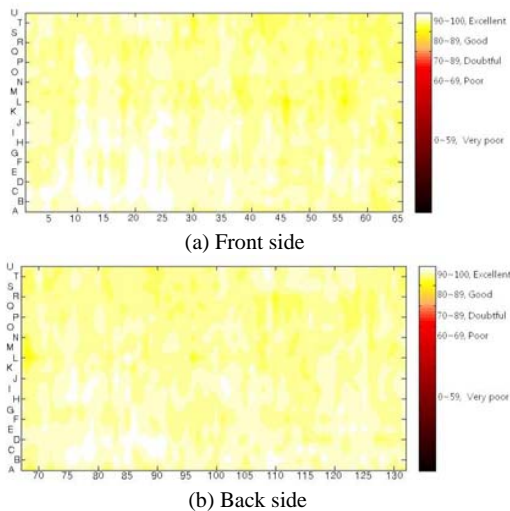

(a) Front side

(b) Back side
Fig. 6 Combined results of the nondestructive test

IV. DESTRUCTIVE TEST RESULTS

The destructive test was conducted by the Korea Institute of Construction Materials, which is a certified testing institution. The test results are shown in Table III.

TABLE III
DESTRUCTIVE TEST RESULTS.

Test Type	Unit	Test Results			Applied Standard	Status
		Sample 1	Sample 2	Sample 3		
Compressive strength test	MPa	28.4	31.2	31.0	KS F 2405-10	Good
Chloride penetration test	mm	7.47	11.49	10.11	KS F 2596-04	Excellent
Carbonation test	%	0.0028	0.0013	0.0018	KS F 2713-07	Excellent

A. Results of the Compressive Strength Measurement Test

The mean of the compressive strength measurement test results was 30.20MPa. It exceeded the design strength of 30.00MPa for LNG storage tanks.

Therefore, the concrete strength of the LNG storage tank cover was considered to maintain the required strength.

B. Results of the Test of the Chloride Content

As shown in Table IV, the maximum chloride content of concrete is suggested in the Standard Specifications for Concrete (2009), [7]. Since post-tension was applied to the subject structure, standards for prestressed concrete were used. The results of the measurement of the chloride content of the three concrete cores had a mean of 0.0019%, which significantly differs from the standard of 0.06%. This means that the LNG storage tank in this study showed no risk of durability deterioration of due to chloride-induced corrosion.

TABLE IV
MAXIMUM CHLORINE ION RATIO IN CONCRETE

CONCRETE TYPE	MAXIMUM CHLORINE ION RATIO (%)
PRESTRESSED CONCRETE	0.06
REINFORCED CONCRETE EXPOSED TO A CHLORIDE	0.15
DRY OR MOISTURE-ISOLATED CONCRETE	1.00
OTHER REINFORCED CONCRETES	0.30

C. Results of the Test of the Neutralization Depth

The mechanism for estimating concrete neutralization is almost the same as that for carbonation, and the results of the test of the neutralization depth were analyzed using the estimation equation suggested in the Standard Specifications for Concrete (2009), [7],which suggests the following carbonation depth limit of corrosion in a steel bar:

$$y_{\lim} = c - c_k \qquad (5)$$

In the preceding equation, $y_{\lim}$ is the carbonation depth limit (mm) of corrosion in a steel bar; c, the design thickness of the coating (mm); and c_k, the margin of the carbonation depth

limit (mm; under a natural environment, 10 mm and under a severe chloride-induced corrosion environment, 25 mm). The design thickness of the coating of the LNG storage tank was 50 mm; and since the tank was located at the seaside, a severe chloride-induced corrosion environment was assumed and accordingly, the carbonation depth limit of corrosion was 25 mm. The equation for the carbonation depth limit of corrosion is as follows:

$$y_p = \gamma_{cd}\alpha_d\sqrt{t} \qquad (6)$$

In the preceding equation, y_p is the estimated carbonation depth (mm); γ_{cd}, the safety coefficient of the equation for the estimated carbonation depth considering variability (usually 1.15, but for super-flowing concrete, 1.1); α_d, the coefficient of the design carbonation velocity ($mm/\sqrt{y}$); and t, the material age (y). There are various equations for the velocity coefficient; and in this study, the neutralization depth value was used to calculate the coefficient of the carbonation velocity. As a result of the substitution of the mean neutralization depth of 9.69 mm, the safety coefficient of 1.15, and the service life of 20 years, the coefficient of the carbonation velocity was calculated as 1.884. Using this velocity coefficient, the time spent for reaching the carbonation depth limit of 25 mm or the total service life was calculated as about 133 years, which means the risk of structure deterioration due to neutralization was considered extremely low.

V. CONCLUSION

The deterioration and performance of the concrete cover of an LNG storage tank were evaluated to manage the tank cover's service life, in accordance with the procedure suggested in Fig. 2 The following conclusions were drawn.

 (1) Based on the width and patterns of the cracks that were observed during the visual inspection of the LNG storage tank, the cracks were considered non-structural cracks. The concrete strength of the suspected areas that were found through the Schmidt hammer test was estimated using the strength estimation equation. The results showed that all the sections had a higher design strength value of 30MPa, which means they had no anomaly.

(2) The results of the ultrasonic pulse velocity test in the suspected concrete areas ranged from 4.01 to 4.49 km/s, which means a normal quality.

(3) According to the test in which concrete cores were used, the mean compressive strength was 30.20MPa, which was almost the same as the design strength. The mean chloride content was 0.0019% and the neutralization depth was 9.69 mm, which significantly differ from the standard specifications for concrete of 0.06% and 25 mm. This means that the deterioration risk caused by the chloride content or the neutralization was extremely low.

(4) The 41.55MPa estimated concrete compression strength from the Schmidt hammer test significantly differed from the 30.2MPa actual concrete compression strength from the destructive tests. This was due to the following reasons: first, to obtain reliable estimated values from the Schmidt hammer test, about 20 hammering strokes at each measurement site were required [10], [11], but only five hammering strokes per measurement site were executed in this study due to the limitations of reality. Second, the neutralization on the surface of the concrete significantly affected the level of restitution in the Schmidt hammer test. Neutralization is more significant on older concrete, and is 50% more severe than on concrete without neutralization[10],[11]. In addition, the material age and the moisture of the concrete also affected the results of the Schmidt hammer test. Therefore, the actual compressive strength could not be determined with only the Schmidt hammer test due to its lack of reliability. Rather than using the Schmidt hammer test to directly estimate the compressive strength, the test can be reasonably used to detect relatively suspected areas.

(4) According to the evaluation of the lifespan expectancy based on the test of the neutralization depth, the estimated total lifespan of the structure was 133 years, which means the risk of deterioration of the structure due to neutralization was considered extremely low during the structure's service life.

(5) In this study, the procedures of the tests, preliminary investigations, nondestructive tests, destructive tests, lifespan expectancy evaluation, and safety evaluation were suggested for the evaluation of the LNG storage tank. The suggested procedures may help evaluate the performance of LNG storage tanks and decide on relevant repairs and reinforcements.

In the inspection of the concrete cover of the Incheon LNG storage tank, normal results were obtained in all the items, and the tank was considered to have maintained the necessary soundness.

In some countries, coating and painting of LNG storage tanks and extension of their lifespan are decided on based on the results of their performance evaluation. In Korea, standards for LNG storage tank performance evaluation and lifespan evaluation, and for the evaluation procedure, which are appropriate to the Korean environment have not been prepared yet, and accordingly, absolutely no performance evaluation has been conducted yet. For example, coating and painting of LNG storage tanks in Korea to prevent deterioration due to chloride-induced corrosion and neutralization are conducted without appropriate evaluations. This is absolutely unreasonable and not found in other countries, and wastes taxes. The concrete cover test procedures that were suggested in this study were proposed to the Korea Gas Corporation to reduce the life cycle cost of their LNG storage tanks. Studies on detailed and reasonable evaluation criteria and standards should be actively conducted at least for the evaluation of LNG storage tanks whose service life will end soon.

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