Development of rapid construction technology for liquified natural gas storage tanks using precast concrete panels as a permanent form

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- Existing construction methods for liquified natural gas (LNG) storage tanks are time consuming and subject to many uncertainties, such as weather conditions and material availability.
- This paper considers possible rapid construction methods for LNG storage tanks and proposes a method using partial-thickness precast concrete panels.
- A full-scale test section of the outer tank wall was constructed using the proposed method and evaluated for strength, stability and constructibility.
- The results indicate that the proposed LNG storage tank construction method using precast concrete panels can reduce construction time by approximately six months without significantly affecting costs.

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The demand for natural gas, an energy resource that accounts for a large portion of global energy consumption, is steadily increasing worldwide. In most parts of the world, such as Europe and North America, land transport is possible and natural gas is supplied through pipelines. However, in areas such as Korea, Japan, and Taiwan, marine transportation is required and the volume of natural gas needs to be reduced to $\frac{1}{600}$ of its original value by liquefying it at temperatures below -160°C (-256°F) before it can be transported by sea. Once transported, the liquefied natural gas (LNG) needs to be stored in LNG tanks. Various design techniques and types of tanks have been developed to store LNG, including single containment tanks, double containment tanks, full containment tanks, and membrane tanks.[1,2] Most LNG storage tanks are full containment tanks consisting of inner and outer tanks.

Figure 1 shows the configuration of a full containment LNG storage tank. The wall liner is installed on the inside of the outer tank wall and acts as a vapor barrier (Fig.1). The inner tank is in direct contact with the cryogenic LNG, so it is made of 9% nickel steel, which is a ductile material at cryogenic temperatures, for safe storage. The outer tank is made of reinforced or prestressed concrete to protect the inner storage tank and to contain accidental LNG spills from the inner tank. The outer tank is generally constructed using cast-in-place (CIP) concrete.

There are several problems and limitations in using the CIP concrete to construct the outer tank for LNG storage. First,

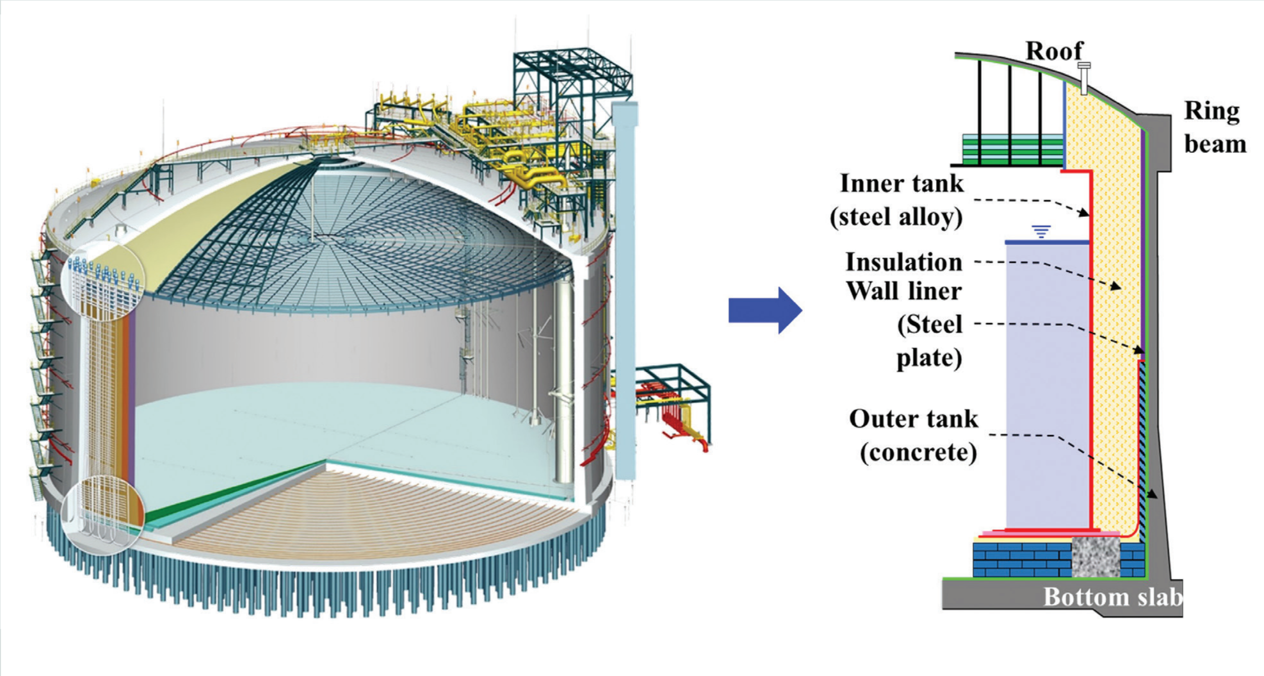


Figure 1. Full containment tank (9% nickel steel type).

LNG storage tanks account for the largest portion of LNG terminal construction, and it is difficult to predict the timing of CIP concrete construction because of changes in the weather conditions, supply of materials, and availability of workers. Overhead costs increase due to delays and significantly reduce economic efficiency.

Second, the outer wall of an LNG storage tank is typically constructed using high-strength concrete with a 40 MPa (5.8 ksi) compressive strength or higher and a large quantity of concrete (10,000 m^3 [350,000 ft^3] or more), thus it is difficult to ensure consistency and proper curing of the concrete. Because quality control is difficult when using CIP concrete, cold joints and shrinkage cracks can occur. In addition, tight tolerances are required to prevent LNG leakage. The precision of the post-tensioning affects the liquid tightness of the LNG storage tank, but it is more difficult to maintain the necessary tight tolerances when prestressing in the field.

Third, because the height of the outer wall of an LNG storage tank is about 40 m (130 ft), there is always the risk of accidents. It is important to simplify and minimize the concrete placement activities in the field— such as reinforcement installation, form installation, and placing concrete via pumps—to improve safety and reduce construction accidents that are caused by falls. New construction techniques that apply precast concrete methods used in other civil engineering fields to LNG storage tanks have been actively developed to solve these problems with CIP concrete construction, as well as reduce construction time.

In this study, a new rapid method for LNG storage tank construction using the partial-thickness precast concrete panels is proposed. Precast concrete panels are chosen for their ability to shorten construction time and improve quality control. The precast concrete panels are used as the outer permanent form and the wall liner is used as the inner permanent form for the outer tank wall. This new construction method allows for the installation of the outer tank wall without temporary forms. As a result, it provides the advantage that inner and outer tanks can be simultaneously constructed after the self-standing wall liner is completed. This method can reduce the construction time by about six months.

Related technology trends

The development of LNG storage tank design technology has mainly focused on large-capacity tanks to maximize economic efficiency. Accordingly, 270,000 m^3 (9,500,000 ft^3) large-capacity LNG storage tanks have been designed and constructed.[3,4] Furthermore, along with the study of materials to develop ultra-high-performance concrete that is resistant to cryogenic temperatures,[5] new technologies for LNG storage tanks are being developed that are economical and that shorten the construction time regardless of capacity. These technologies are being designed to account for various conditions, such as LNG bunkering and construction in polar regions.[6]

Various methods have been studied to reduce the construction time of LNG storage tanks. The typical construction time of a 200,000 m^3 (7,100,000 ft^3) LNG storage tank is about

39 months. Construction methods using jump forms or slip forms have been developed to shorten the construction time.[7,8] In recent years, a precast concrete method that has been used to construct concrete water tanks has been studied for application to the construction of LNG storage tanks. Concrete water tanks are constructed using vertical precast concrete panels, and joints between adjacent panels are constructed using the wet-joint method. Because water tanks are smaller than LNG storage tanks, the precast concrete panels are lighter and easier to install on-site than they would be for an LNG storage tank. When the precast concrete method is applied to a cylindrical tank, a silo tank is constructed by arranging precast, prestressed concrete panels along the circumference of the tank.[9] Precast concrete panels have been used to construct LNG storage tanks where both inner and outer tanks were constructed using vertical precast concrete panels, and then prestressing was applied along the circumference.[10] Hjorteset et al.[11] and Hoyle et al.[12] recently presented a composite concrete cryogenic tank that used vertical precast concrete panels finished with circumferential prestressing and shotcrete to construct the inner and outer tanks for LNG storage. The composite concrete cryogenic tank construction method is advantageous because it reduces construction costs by about 10% to 15% and shortens the construction time by about six to eight months.

In order to construct the inner and outer tanks simultaneously, two methods used to construct steel oil tanks are being studied to construct the inner tank or wall liner. The first method is a bottom-up method, in which steel plates are stacked along the tank circumference using cranes. Another method is the top-down method, in which automatic welding and lifting for steel plates are repeatedly applied from the ground using hydraulic jacking equipment.[13] Simmons and Dyson[14] developed a new construction method using the wall liner as a permanent form and applying a top-down method. In this method, the wall liner, which is used as the permanent form for the inside of the outer tank, is constructed first, and then the CIP concrete method is used to construct the outer tank. In addition, Yamada and Kato[15] developed a method to construct the inner and outer tanks simultaneously by continuously raising the inner steel plate using the jack-climbing method and constructing the outer tank with the conventional CIP method. This method can reduce construction time by about 14 months.

Development of rapid construction technology

Existing construction procedure for LNG storage tanks

The outer tank of an LNG storage tank is usually constructed according to the following steps:

1. First, the foundation is constructed.

2. Then, the corner ring is constructed prior to the construction of the wall and bottom slab (circular portion), to ensure the effective development of prestress around the structure at the wall and bottom slab joint. The bottom slab and wall (layer 1) form a reversed T shape. Reinforcing bars, ducts for post-tensioning, and anchors are installed. Fixed formwork provides the accurate structural configuration of the corner ring.

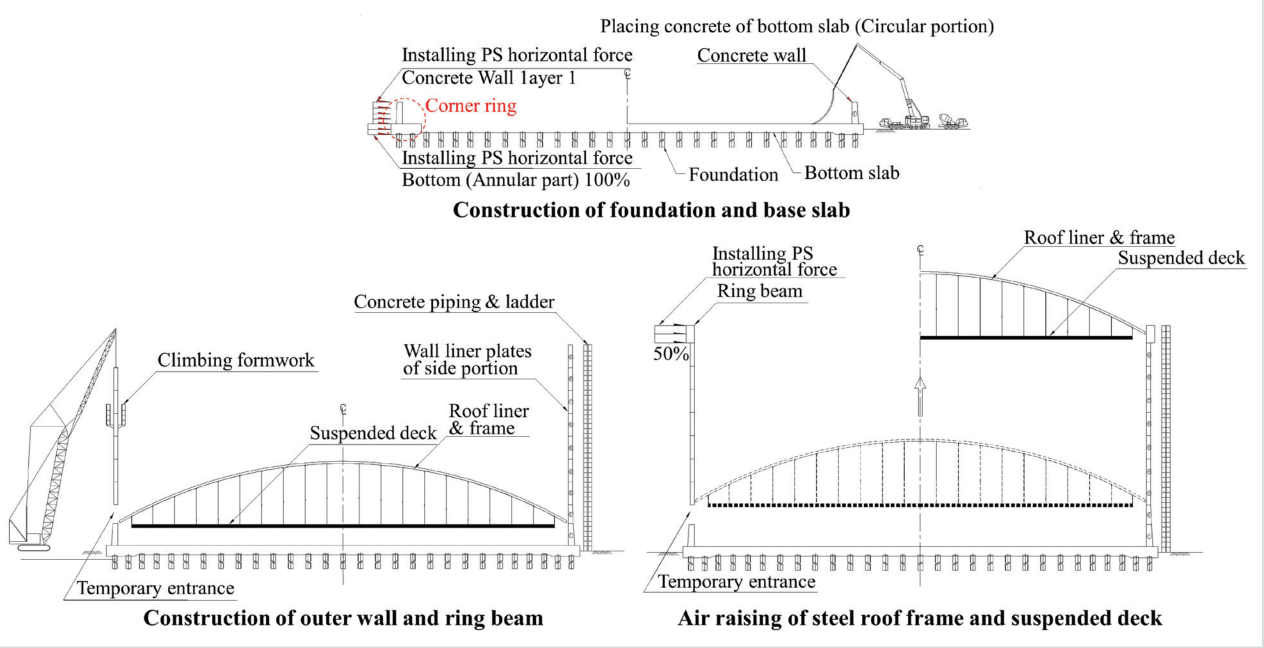


Figure 2. Existing construction procedure for LNG storage tanks. Note: LNG = liquified natural gas, PS = prestressing.

3. After the corner ring has cured, full prestressing of the bottom slab and prestressing of about half of the wall (layer 1) is performed using circumferential prestressing tendons. To prepare the bottom slab (circular portion) for construction, reinforcing bars are placed and electrical base heating is installed at the same time as corner ring construction.

4. When the prestressing work for the corner ring is complete, the bottom slab (circular portion) concrete is placed (**Fig. 2**).

5. After the corner ring structure has cured, the wall climbing form above layer 1 is prepared. Reinforcing bars and ducts are installed before the climbing form and scaffolding is assembled. The prestressed concrete walls above layer 1 are built using the climbing form. The reinforcing bars, ducts, and anchorages are installed to construct the ring beam in the next step. The fixed formwork provides the accurate structural configuration of the ring beam (Fig. 2).

6. The prestressing tendons in the ring beam are installed in two steps. First, half of the prestressing tendons in the ring beam are installed before proceeding with the roof construction; then the remaining prestressing tendons are installed after the first step of the concrete roof construction.

7. The steel roof and suspended deck are installed within the prestressed concrete outer tank after the wall construction is complete. The steel roof is built on the bottom slab and raised up into its designated position using air pressure provided by a number of blowers. The steel roof is temporarily welded at the top of the concrete wall within a few hours of being raised before it is connected permanently (Fig. 2).

8. Concrete is placed above the steel roof, with the steel forming the roof liner below the concrete roof. The concrete roof is constructed in two steps. The first layer of half of the roof concrete is placed, the remaining prestressing tendons of the ring beam are installed, and then the second layer of half of the roof concrete is placed.

9. The inner tank is installed after the concrete roof is completed. The concrete outer wall has large temporary entrances to provide access for the inner tank construction. Before the prestressing tendons are tensioned, the temporary entrances must be closed using self-consolidating expansive concrete. Next, the vertical wall tendons and the horizontal wall tendons are post-tensioned up to the design force. The ducts are grouted immediately after prestressing to avoid corrosion due to chloride attack. Then, the functional performance of the inner tank is tested using the hydraulic test.

10. After the verification test is completed, the annular space between the prestressed concrete outer tank and inner tank is filled with perlite particles as insulation. The concrete structure will be closely monitored and controlled according to a quality assurance program developed for prestressed concrete outer tanks.

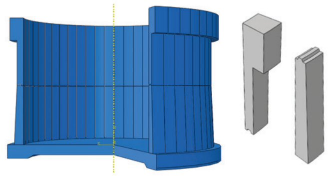
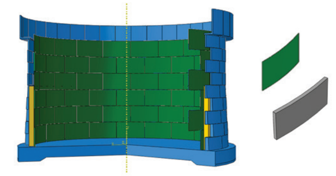
Selection of rapid construction method

The existing construction method has proved successful on quite a number of LNG tank construction projects. However, the existing construction procedure requires that the outer wall and steel roof construction be completed before the inner tank can be constructed. In addition, it is difficult to reduce the construction time for the outer wall because of the time required for the installation and removal of forms. Therefore, to improve the existing construction method, a new LNG storage tank construction method using precast concrete technology was developed. The goal of the new precast concrete panel construction method was to simultaneously improve the economics and constructibility of LNG storage tanks. Many factors, such as panel shape, feasibility of fabrication, precast concrete panel weight for ease of lifting, and joint details between panels, were considered. After discussing various ideas, such as vertical panels, horizontal panels, and T-section panels, two methods were chosen to be evaluated, and the final construction method was selected using a detailed comparison of each precast concrete panel option. The two-piece split vertical panel is a full-depth precast concrete option for the outer tank wall. The partial precast concrete option is a partial-thickness precast concrete panel used with the wall liner as permanent formwork to construct a composite precast and cast-in-place concrete outer tank wall (**Table 1**).

Benefits of the two-piece split vertical panel method include minimizing the vertical joints and reducing the panel weight, which facilitates lifting and installation by crane. However, the two-piece split vertical panel method requires working at heights to place panels and connect the joints of the upper and lower panels, and the continuity of vertical reinforcement in the upper and lower joint connection of the panels is a problem. Benefits of the precast concrete panel method include reducing the number of joints and improving the connection of the base slab to the outer wall. This is a new construction method in which the wall liner is constructed first, and then the wall liner and precast concrete panels are used as a permanent form. Because the wall liner of this method must be designed to be self-standing and support the construction loading due to CIP concrete placement, it is necessary to decide the thickness of the wall liner and the specific construction method to ensure the wall liner's structural stability.

The two-piece split vertical panel method also can increase the speed of outer tank construction because the panels are larger, which reduces the number of panels that must be placed. Alternatively, the panels for the split vertical method have greater weights compared with the partial-thickness precast concrete panels, which requires additional area for storing panels, larger cranes to place the panels, and corresponding cost increases. In addition, the two-piece split verti-

Table 1. Detailed comparison of two-piece split vertical panel and partial precast concrete pane methods

Method		Two-piece split vertical panel	Partial precast concrete panel
			
Panel	Dimensions	2.535 × 0.750 × 18.750 m	2.300 × 0.100 × 3.750 m
		Number of circumferential sections: 108	Number of circumferential sections: 120
		Number of vertical sections: 2	Number of vertical sections: 10
	Approximate weight	90 tonnes each	3 tonnes each
	Quantity	216	1200
Factory site	Casting bed	Large panel sizes require large casting beds and cost to set up a factory	No need for specialized casting bed as the panel size is small
	Loading site	• Number of panels that can be stacked is limited by panel weight • Requires significant panel loading area	• Reduced panel weight allows number of panels that can be stacked to be two or three levels • number of panels requires significant panel loading area
Transport	Safety	Risk of cracking due to excessive panel size and weight	Because the panel is thin, cracks may occur during transport
Construction	Weight of crane	Requires a crane capacity of 300 tonnes or more	Not limited by crane capacity
	Lifting and unloading	• Increased cost and construction time for panel handling • Step-by-step review and reinforcement design required from lifting to unloading	• Light weight makes it easy to lift and unload • Faster jobs available (speeds up construction in general)
	Temporary construction equipment	• Temporary bracing required to prevent overturning due to weight and size of panels • Two-piece construction increases the temporary bracing	• Cast-in-place concrete work requires a working platform similar to that required for the existing construction method • Requires temporary bracing for permanent form installation
	Formwork	• Forms required at vertical and horizontal joints	• Wall liner (permanent form) must be built first • No temporary form installation and dismantling
Connection	Connection of reinforcing bars, panels, etc.	• Vertical reinforcing bars: shear key, coupler, dry or wet joint • Circumferential reinforcing bars: wet joint (loop splice, etc.) • Connection between base slab and outer wall: hinge or new method	• Continuity of vertical and horizontal reinforcement is ensured in the cast-in-place section • Precast concrete panel joints need to be considered
Construction time	Field assembly	Expected to reduce typical tank construction time by about five months	Expected to reduce typical tank construction time by about six months

Note: 1 m = 3.281 ft; 1 tonne = 1.102 tons.

cal method can cause structural stability problems because the vertical reinforcing bars are not continuous unless a special connection device is used. In contrast, although more precast concrete panels are required to construct the outer tank for the partial precast concrete panel method, there are advantages in terms of lifting and ease of installation because the panels are lighter, and the partial precast concrete panel method can be applied to a wide variety storage tanks regardless of capacity. In addition, because the working platform is similar to that required for the climbing form used in the existing construction method, no additional working platform design is required. Furthermore, the reinforcing bars and tendons are continuous in the partial precast concrete panel method, and the problem of ensuring that the tank is watertight can be solved. For these reasons, the partial precast concrete panel method was chosen as the proposed construction method.

In the partial precast concrete panel method, the wall liner, including the studs, is constructed using the hydraulic jacking method typically used for steel shell tank construction. The wall liner must be self-standing before the precast concrete panels are placed to construct the outer tank. Precast concrete panels are manufactured as necessary for the outer tank of the LNG storage tank and assembled after they are transported to the site. For the on-site assembly of the precast concrete panels, vertical and horizontal joints are treated using shear keys, epoxy resin, and backup rods (**Fig. 3**). Tie rods are used between the wall liner and precast concrete panels to secure the panels and ensure structural stability when placing CIP concrete between the wall liner and panels. When concrete is placed, a working platform similar to that used with the existing construction method's climbing form is used. However, unlike the existing method's climbing form there is no temporary formwork and the construction time can be shortened because there is no installation and dismantling of forms.

Proposed construction procedures

Figure 4 shows the stages for the proposed LNG storage tank construction method. First, the foundation and bottom-slab installation work are completed in the same way as the existing construction method. The foundation and bottom slab installation work includes placing reinforcement, installing sheath tubes, and installing an electric base heating system. In addition, prestressing is applied to the annular part of the

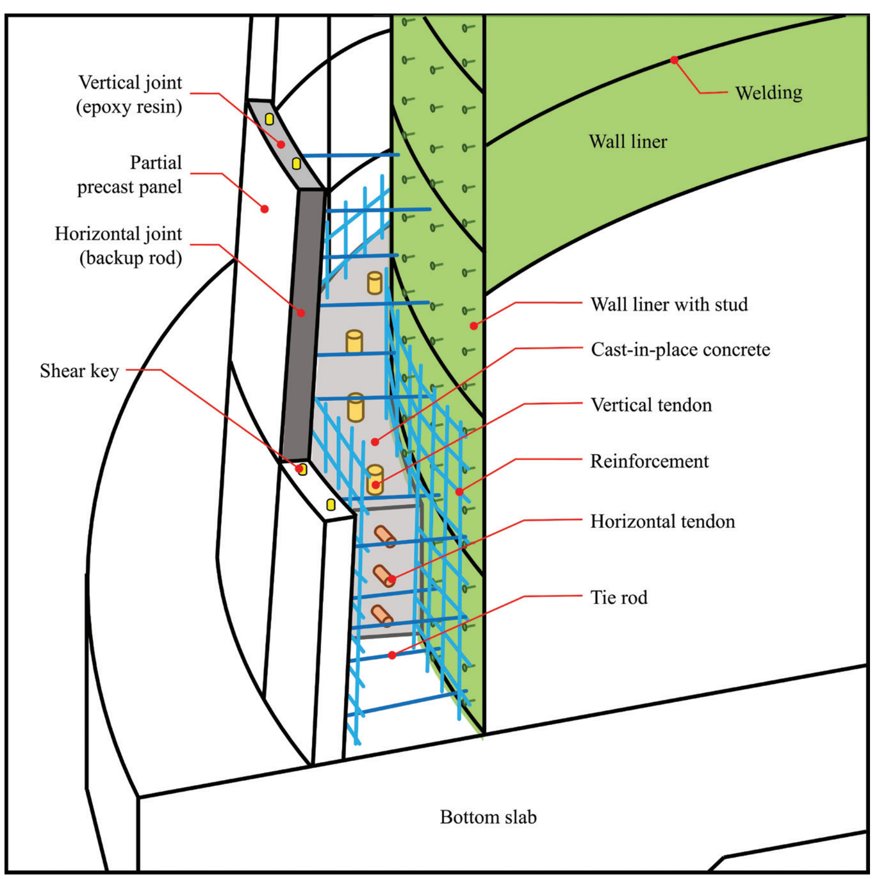


Figure 3. Conceptual drawing of outer tank construction using partial-thickness precast concrete panels.

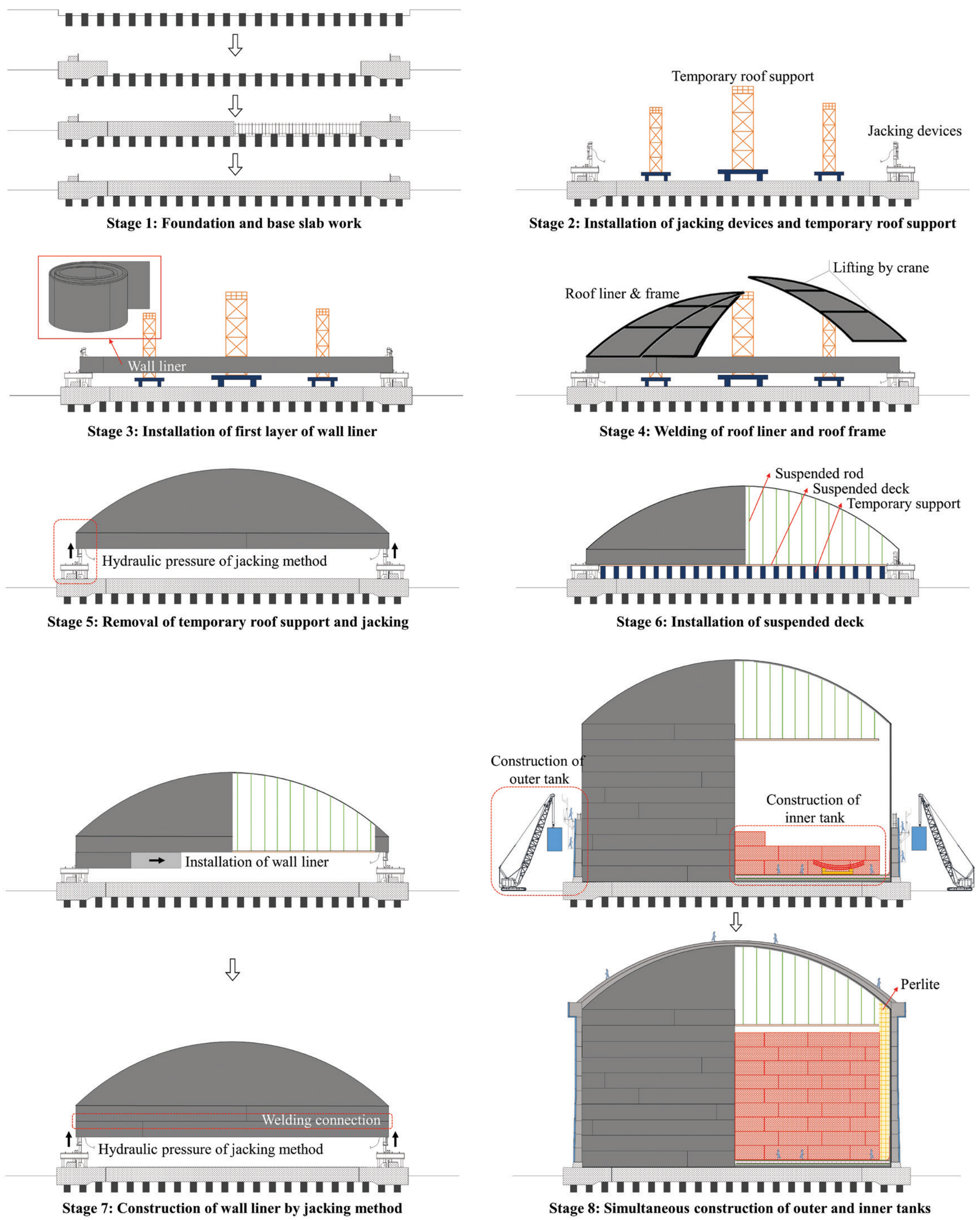


Figure 4. Proposed rapid construction procedure for LNG storage tanks. Note: LNG = liquified natural gas.

bottom slab in some cases, and the lowest part of the outer wall, called a kicker, is also constructed.

After the foundation and bottom-slab work is completed, jacking equipment is installed to construct the self-standing wall liner, and temporary roof supports are installed to weld the roof liner to the wall liner. The wall liner is constructed from steel plates that have a standard size and a curvature. Jacking equipment allows for self-standing construction of the wall liner using the top-down method.

Then the jacking equipment is installed. The first layer of the wall liner is constructed on the bottom slab using prefabricated steel plates. When the first layer of wall liner is completed, the prefabricated roof liner and roof frame are lifted using a crane, then placed on the temporary roof supports and welded to the wall liner.

After the roof structural members are welded to the wall liner, the temporary roof supports are dismantled and the wall liner and roof structure are raised together using the hydraulic jacking equipment. The next step is to install temporary supports on the bottom slab for construction of a suspended deck. The suspended deck is connected to the roof liner using suspended rods. The equipment and structural materials required for construction of the suspended deck and rods can be moved to the inside of the tank after the wall liner is lifted using jacking equipment.

When the construction of the suspended deck and rods are completed, the temporary supports are dismantled. Because construction of the self-standing wall liner is a priority, after the suspended deck and rods are installed, the remaining layers of the wall liner are sequentially constructed using the jacking method. The jacking method consists of lifting the first layer of the wall liner, then installing and welding the second layer under the first layer, and then both layers are lifted together using the hydraulic jacking equipment. The joints between the two wall liner layers can be automatically or manually welded.

After the wall liner is erected, temporary openings are constructed to provide access for the equipment and structural members required for the inner tank construction. Bottom insulation and corner protection made with 9% nickel steel is installed inside the wall liner before the inner tank is constructed. At the same time that the bottom insulation and corner protection is installed, the outer tank is constructed using precast concrete panels. The inner and outer tanks are then constructed simultaneously.

The proposed construction sequence is considerably different from the existing construction method for LNG storage tanks and can be expected to shorten the construction time. **Figure 5** shows the detailed construction procedure of the outer tank with precast concrete panels. Step 1 includes the installation of reinforcing bars and sheath tubes. The subsequent processes—such as prestressing work, roof concrete placement, hydrostatic test, insulation work, and finishing work—follow the same procedure as that used in the existing construction method for LNG storage tanks.

Design of partial-thickness precast concrete panels and wall liner

Design of precast concrete panels To design the precast concrete panels for the outer tank of the LNG storage tank, a numerical analysis study was performed considering the lateral pressure of fresh concrete on the panels during concrete placement as specified in the American Concrete Institute's *Guide to Formwork for Concrete* (ACI 347-04 and other references).[16–18] Generally, the lateral pressure of fresh concrete on the panels required for the wall construction should be calculated according to Eq. (1). For

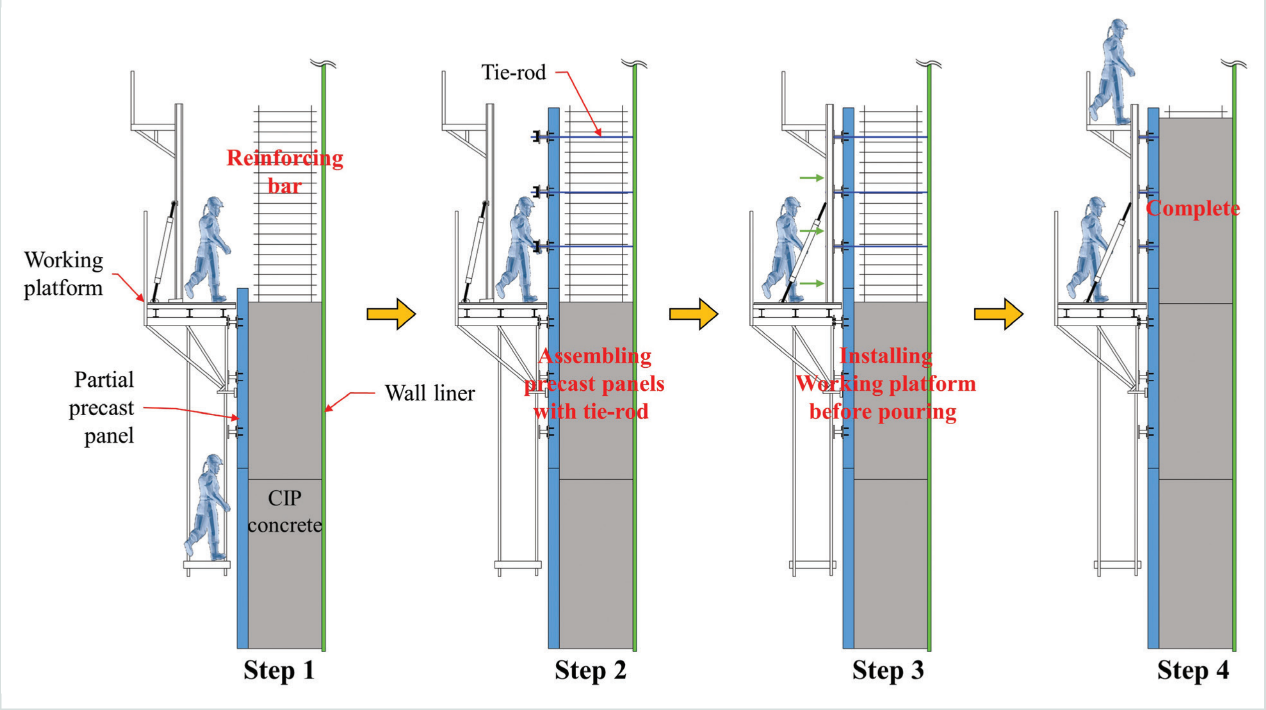


Figure 5. Construction procedure for outer tank with partial-thickness precast concrete panels. Note: CIP = cast-in-place.

walls with a rate of placement of less than 2.1 m/hr (6.9 ft/hr) and a placement height not exceeding 4.2 m (13.8 ft),

$$P = C_w \times C_c \times \left[7.2 + \left(\frac{785 \times R_p}{T_c + 17.8} \right) \right] \geq 30 \times C_w \qquad (1)$$

where

P = lateral pressure of fresh concrete

C_w = density coefficient

C_c = chemistry coefficient

R_p = rate of placement

T_c = temperature of concrete

Equation (1) has a minimum value of $P = 30C_w$ kPa, but in no case can P be greater than ρgh, where ρ is the density of concrete, g is gravitational acceleration, and h is the height of fresh concrete.

However, the calculated lateral pressure acting on the outer tank wall of the LNG storage tank was expected to be less than 30 kPa (4.4 psi), considering the rate of placement and temperature of concrete. Therefore, the precast concrete panels were designed by applying the minimum lateral pressure of 30 kPa specified in ACI 347-04. In addition, the vertical prestressing load was applied to the precast concrete panels and their structural safety was evaluated by comparing the calculated stress, considering prestress losses, with the allowable stress. As a result, the minimum required thickness of the precast concrete panels was determined to be 100 mm (4.0 in.), taking into account the minimum thickness that could serve as a form. To simplify the fabrication of panels, the inner face of the panels was constructed as a plane surface and the outer face was constructed to create the curvature of the outer tank wall. **Figure 6** shows the design drawing of a precast concrete panel as determined from the structural calculations.

The outer tank constructed with partial-thickness precast concrete panels is not considered to be a fully composite structure with the CIP concrete and precast concrete panels. The precast concrete panels behave with the CIP concrete and the shear connection reinforcing bars; however, they are not considered to be fully composite because a joint gap may occur between adjacent precast concrete panels. The joints of adjacent precast concrete panels are connected by a backup

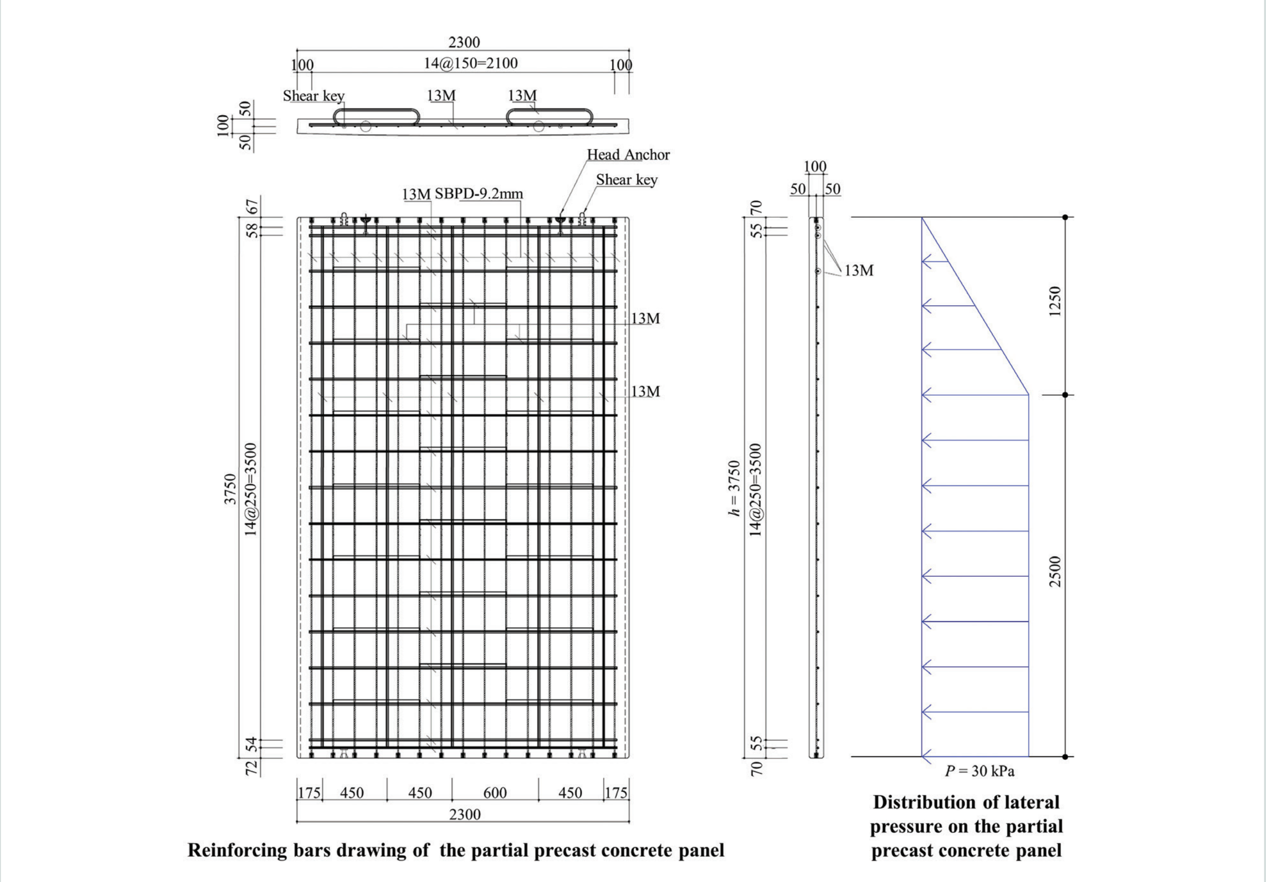


Figure 6. Design drawing of partial-thickness precast concrete panel. Note: All dimensions are in millimeters. SBPD = steel bars for prestressed concrete. 13M = no. 4; 1 mm = 0.0394 in; 1 kPa = 0.145 psi.

rod in the circumferential direction and a shear key and epoxy resin in the vertical direction. Therefore, the construction safety of precast concrete panels in compression, which is generated by the post-tensioning of CIP concrete, should be evaluated and considered in the outer tank design.

The precast concrete panels were 2.3 m (7.5 ft) wide, and 120 panels were required in the circumferential direction for a 200,000 m^3 (7,100,000 ft^3) LNG storage tank. This configuration implies that there is a margin for total compressive deformation of 120 mm (4.7 in.) in the circumferential direction because the gap between adjacent panels is approximately 1 mm (0.0394 in.).

Because the panel connection in the vertical direction is constructed with epoxy resin between the panels, all of the upper and lower panels are connected so that the compression force due to the vertical load is fully transferred to the panels as well as CIP concrete. Therefore, the compressive stress in the panels caused by relative displacement at each layer of the outer wall and ring beam were compared with the allowable compressive stress.

The results of the analysis showed that the maximum strain in the circumferential direction was 2.4×10^{-4}, and the total deformation in the circumferential direction was calculated to be 66 mm (2.6 in.). In other words, sufficient structural safety and constructibility were ensured because the total deformation was less than 120 mm, which is the margin for total displacement in the circumferential direction. In the vertical direction, a maximum compressive stress of 14.4 MPa (2.1 ksi) occurred at the second layer. Because this value is less than the allowable compressive stress of 24 MPa (3.5 ksi), construction safety was ensured.

Design of wall liner The buckling analysis of the wall liner under self-weight is one of the considerations for determining the wall liner thickness and for evaluating structural stability for a self-standing wall liner constructed using jacking equipment. Therefore, it is necessary to determine whether buckling occurs by calculating the self-weight of the wall liner considering its thickness. The buckling stress was calculated using a linear buckling analysis based on the analytical solution specified in National Advisory Committee for Aeronautics 874's *A Simplified Method of Elastic-Stability Analysis for Thin Cylindrical Shells* and 3783's *Handbook of Structural Stability, Part III—Buckling of Curved Plates and Shells* and verified by comparison with the results obtained from a numerical analysis performed using Abaqus software.[19–21] The buckling stress σ_{cr} of a cylindrical wall liner subjected to vertical load can be expressed as follows:

$$\sigma_{cr} = \frac{\kappa \pi^2 E t^2}{12(1-v)L^2}$$

where

κ = buckling coefficient

E = elastic modulus

t = thickness of circular cylinder

v = Poisson's ratio for material

L = length of circular cylinder

The wall liner can be considered a circular cylindrical shell under compression, with the compression due to self-weight. The theoretical solution of buckling can be simplified by defining a parameter to represent the dimensions of the shell Z and a parameter to represent the stress state of the shell k. The parameter Z representing the dimensions of the shell is defined in the following equation.

$$Z = \frac{L^2}{rt}\sqrt{1-v^2}$$

where

r = radius of curvature

The circular cylindrical shell can be divided into three ranges: short-cylinder range ($L^2/rt < 1$), transition-length range ($1 < L^2/rt < 100$), and long-cylinder range ($L^2/rt > 100$).

If L^2/rt is within the long-cylinder range, the value of k representing the stress state of the shell satisfies Eq. (2). Based on the theoretical analysis method, the wall liner analyzed in this study is in the long-cylinder range and

Table 2. Safety factor for buckling stress of the wall liner

Thickness, mm	Roof weight, kN	Self-weight, kN	Buckling stress σ_{cr}, MPa	Analytical P_{cr}, kN	Numerical P_{cr}, kN	Safety factor
5	9810	4111	14.01	19,014	19,419	1.4
6		4933	16.81	27,380	27,487	1.9
7		5755	19.61	37,267	37,545	2.4
8		6578	22.42	48,675	49,363	3.0
9		7400	25.22	61,605	62,436	3.6

Note: P_{cr} = buckling load. 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi

$$k = \frac{4\sqrt{3}}{\pi^2} Z = 0.702Z \tag{2}$$

Table 2 lists the self-weight, buckling load, and safety factor for several wall liner thicknesses. The error rate of the analytical solution compared with the numerical solution is approximately 2%.

According to the Architectural Institute of Japan,[22] the required safety factor for the buckling of cylindrical storage tanks is 2.25 for long-term loading below the yield stress and 1.5 for short-term loading except for in earthquakes. Therefore, to achieve a safety factor of 2.25 or more, a thickness of at least 7 mm (0.28 in.) is considered appropriate; however, in this study, a thickness of 9 mm (0.35 in.) was chosen to improve constructibility of the wall liner.

In addition to the linear buckling analysis, nonlinear buckling analyses were conducted to evaluate local buckling of the wall liner. Nonlinear buckling analysis must be performed carefully because external loads or self-weight in forms due to construction error or eccentricity are not uniformly applied to most structures during actual construction.

Nonlinear buckling analysis is divided into two types: prebuckling and postbuckling. Prebuckling analysis requires checking the linear buckling mode and applying the load from the static to the critical buckling load. In most nonlinear cases, buckling occurs before the linear critical buckling is reached. Therefore, prebuckling is used to obtain a critical buckling load considering nonlinearity. Postbuckling continues to be analyzed even after the buckling occurs during the static analysis stage and is used to check the behavior after the buckling considering nonlinearity.

For the nonlinear buckling analysis, the verified model used for the linear buckling analysis was applied and the self-weight of the wall liner, linear buckling load, and nonlinear buckling load were compared. The results of the nonlinear buckling analysis showed that local buckling occurred near the point of application of the linear buckling load (**Fig. 7**). Furthermore, it was confirmed that the vertical load (17,210 kN [3870 kip]) acting on the wall liner during construction is significantly less than the buckling load (61,605 kN [13,850 kip]). Therefore, local buckling does not occur in the wall liner if only self-weight is considered.

Effect of the proposed construction method on construction time and costs

The proposed construction method using the precast concrete panels and wall liner as a permanent form can reduce the construction time by approximately six months compared with the existing method by enabling simultaneous construction of the inner and outer tanks. In the existing construction method for LNG storage tanks, the inner tank is constructed after bottom slab concrete placement, outer tank construction, and air raising of the roof. In contrast, the inner and outer tanks are constructed simultaneously after the construction of the bottom slab and self-standing wall liner are completed in the proposed rapid construction method using precast concrete panels.

From an economic point of view, the climbing form used in the existing construction method is essential equipment that serves as a temporary form for placing the concrete for the outer tank. However, because the proposed construction method uses the precast concrete panels and wall liner as a

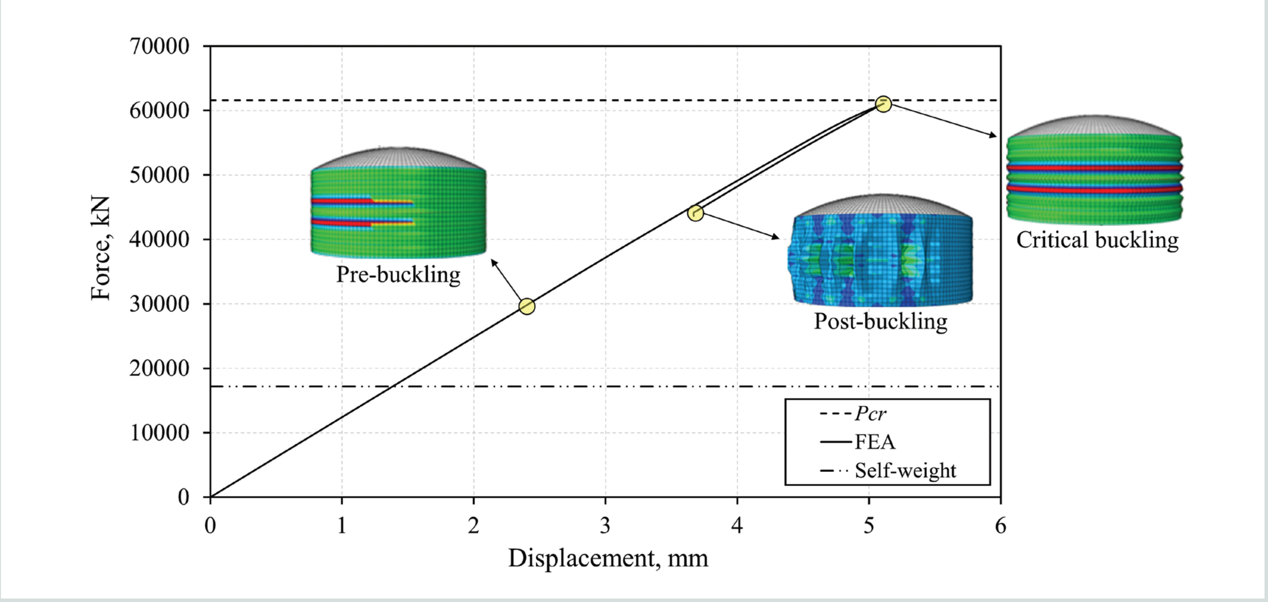


Figure 7. Nonlinear buckling analysis of the wall liner. Note: FEA = finite element analysis; P_{cr} = buckling load. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

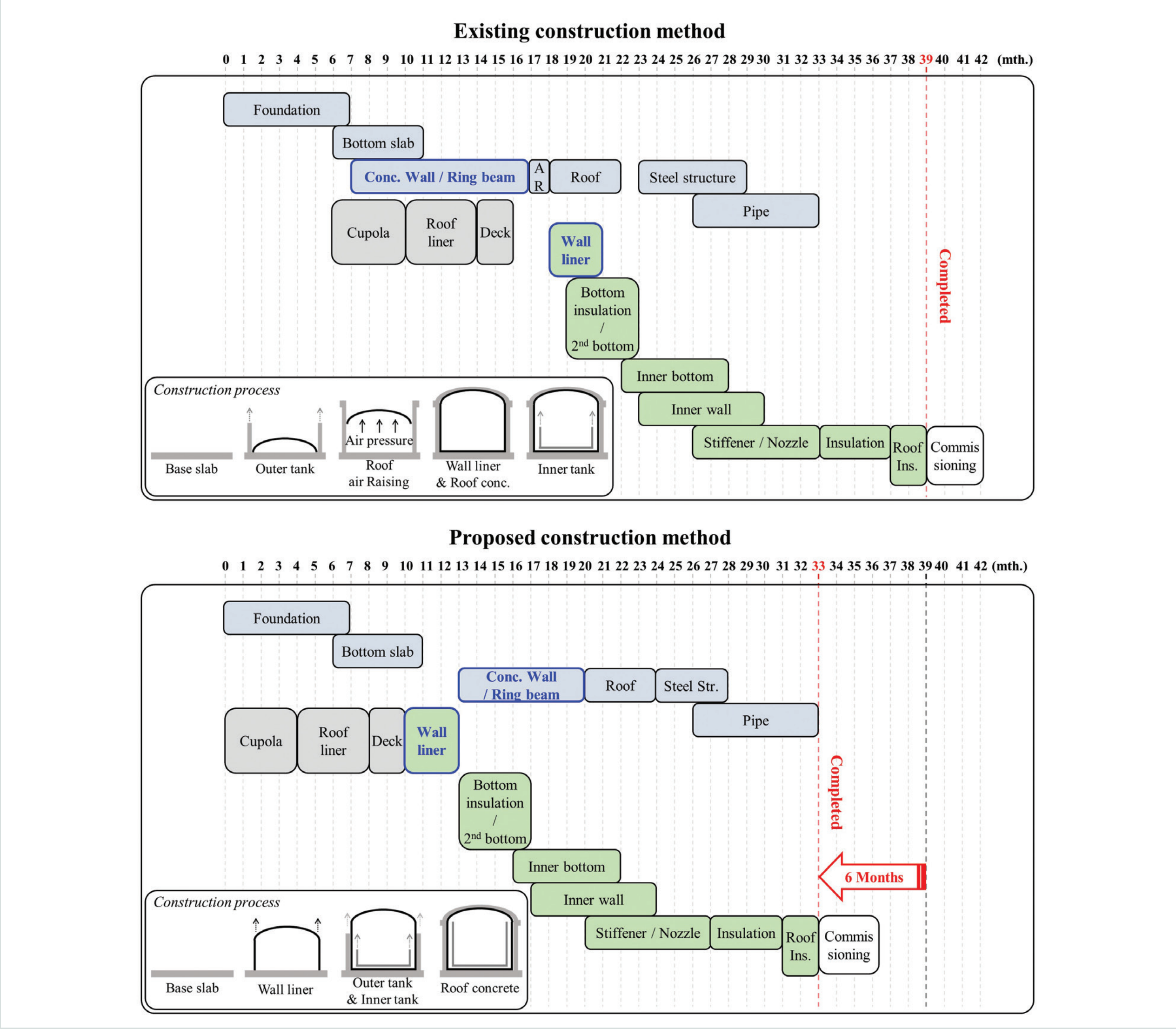


Figure 8. Work schedule comparison between the existing and proposed construction methods. Note: AR = air raising.

permanent form, installation and dismantling of temporary forms is not required and construction can be performed using simple working platforms similar to those used in the existing construction method. Therefore, the construction time can be drastically reduced using the proposed construction method compared with the existing construction method with minimal change in cost. **Figure 8** shows the overall work schedules for the existing and proposed construction methods for LNG storage tanks in more detail.

Full-scale outer tank wall test section

Overview

A test section was constructed to investigate the problems associated with the construction, stability, and applicability of constructing the outer concrete tank wall with partial precast concrete panel technology. The test section was constructed for a portion of an outer tank wall based on an existing 200,000 m^3 (7,100,000 ft^3) LNG storage tank. The test section was 10 m (33 ft) tall and had 12 precast concrete panels that were sized to be reasonable for judging the construction performance and structural stability of the proposed construction method. In addition, to evaluate the field applicability and constructibility of the panels, layer 1 was 2.5 m (8.2 ft) tall, while layers 2 and 3 were each 3.75 m (12.3 ft) tall, which is the same as the layer height for the existing 200,000 m^3 LNG storage tank. For accurate comparison of both methods and to check the constructibility, the test section had the same CIP curing time as the existing LNG storage tank.

Full-scale outer tank wall test section construction

Figure 9 shows the fabrication and construction of the test section for the outer tank wall. The precast concrete panels

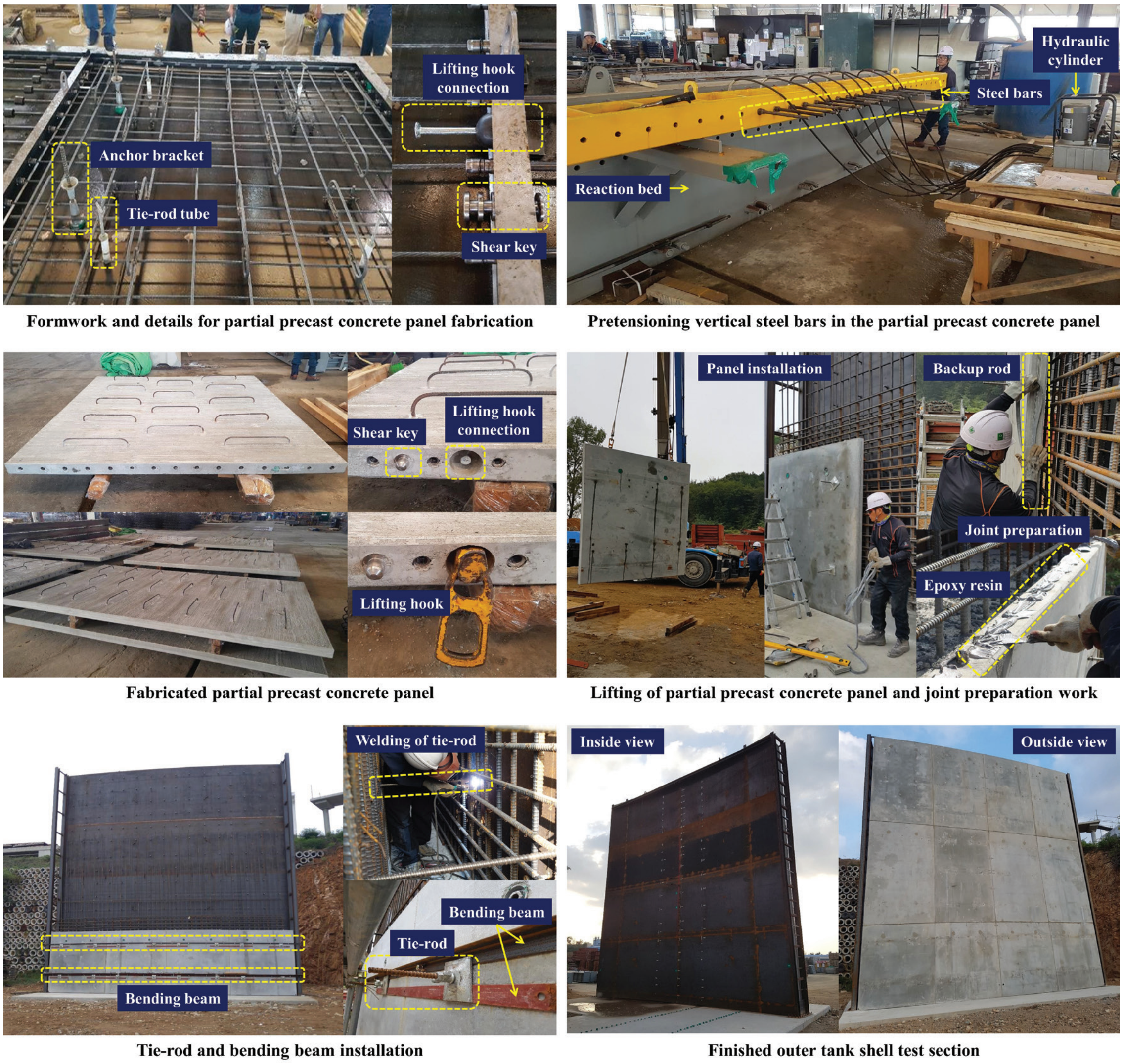


Figure 9. Construction sequence of outer tank shell test section.

were fabricated with the reinforcement, steel bars for pretensioning, lifting hooks, shear keys, bracket anchors, and tie-rod retaining pipes set in the forms. All of the necessary elements were installed in the forms, and then the vertical steel bars in the panel were pretensioned. After applying the prestressing forces to the vertical steel bars, concrete with a design strength of 40 MPa (5.8 ksi) was placed. The concrete was placed and vibrated in the forms at the same time.

The 9 mm (0.35 in.) thick wall liner was constructed with welded studs at 600 mm (24 in.) intervals along the curvature of the wall liner and assembled without jacking because of the test section's small size. After the wall liner was installed, the precast concrete panels were lifted into place and set up using a crane; then, the joints were treated with a backup rod for the horizontal joints and epoxy resin was applied to the vertical joints. After the panels were installed and the joints were prepared, tie rods and bending beams were installed to prevent overturning of the panels. Next, concrete was placed between the panels and the wall liner. This process was used for each layer. The CIP concrete was placed for the previous layer before panels were placed for the next layer.

Constructibility check of test section

The purpose of the test section was to compare the analysis results for the structure to the actual measurements. However, it is also important to check for unexpected conditions that may occur during construction using the proposed method to ensure that the construction can proceed smoothly. Therefore, in addition to taking measurements to compare with the analysis results, various issues and concerns that could arise with the proposed construction methods were discussed in advance and identified for evaluation during the test section construction. The constructibility concerns can be divided into access and constructibility, concrete pressure, and connections.

Access and constructibility First, the reinforcing bar constructibility and concrete placement environment were identified as concerns. It is easy to transport reinforcing bars with a tower crane for constructing tanks using the existing construction method with the climbing form system because the forms can be opened from both the inside and the outside of the tank wall. In addition, in the climbing form system, the inner and outer reinforcing bars and concrete can be placed from either the inside or the outside of the outer wall.

However, in the partial precast concrete panel method, reinforcing bar work and concrete placement can only be performed from the outside of the wall because the wall liners are self-standing on the inside face of the outer wall and are placed in advance. As a result, the concern was that construction was likely to be delayed because of the difficulty of transporting straight reinforcing bars and the narrow work space for placing concrete.

However, the results of the test section construction showed that it was not difficult to transport the straight reinforcing bars using a crane. In addition, as with the conventional method, the outer reinforcing bars were placed after the inner reinforcing bars to maintain the spacing between the inner and outer reinforcing bars in the outer tank wall, and the reinforcing bar assembly for the outer wall was not problematic. Meanwhile, the waiting time for concrete curing was reduced because the precast concrete panels supported the outer wall structure. That means that the partial precast concrete panel method does not have to wait as long for the concrete to cure fully before moving on to the next layer of construction. The weight of each panel was relatively low, thereby making it easy to perform lifting and unloading operations by crane.

Concrete pressure Second, the structural safety of the panels against concrete pressures and the connectivity between the panels were confirmed. In general, it is important not only to construct a form for wall construction but also to ensure that each form is securely fastened to withstand the concrete pressure. In the proposed construction method, steel bars were inserted into the panel and pretensioned to provide the structural safety of the panel. In addition, to provide the connection between panels, the vertical connections on the panels were fitted with a shear key and epoxy resin and backup rods were used to prevent leakage at the horizontal connections on the panels. Moreover, tie rods and bending beams were installed in the same way that was used with removable forms so that the panel connections would not be damaged due to the lateral pressure due to fresh concrete. As a result, the panel assembly and CIP concrete construction were safely completed during test section construction.

Connections Finally, it was verified that the integrity of the connection between the precast concrete panels or wall liner and CIP concrete portions of the outer tank wall was maintained. If the panel or wall liner and CIP concrete sections are not acting compositely, prestressing could result in delamination of these components. To prevent delamination, the inner face of the panels was fabricated with a rough surface and additional shear connectors (loop reinforcing bars) were formed with the panels and extended into the CIP concrete section; studs were installed on the wall liner to promote composite behavior.

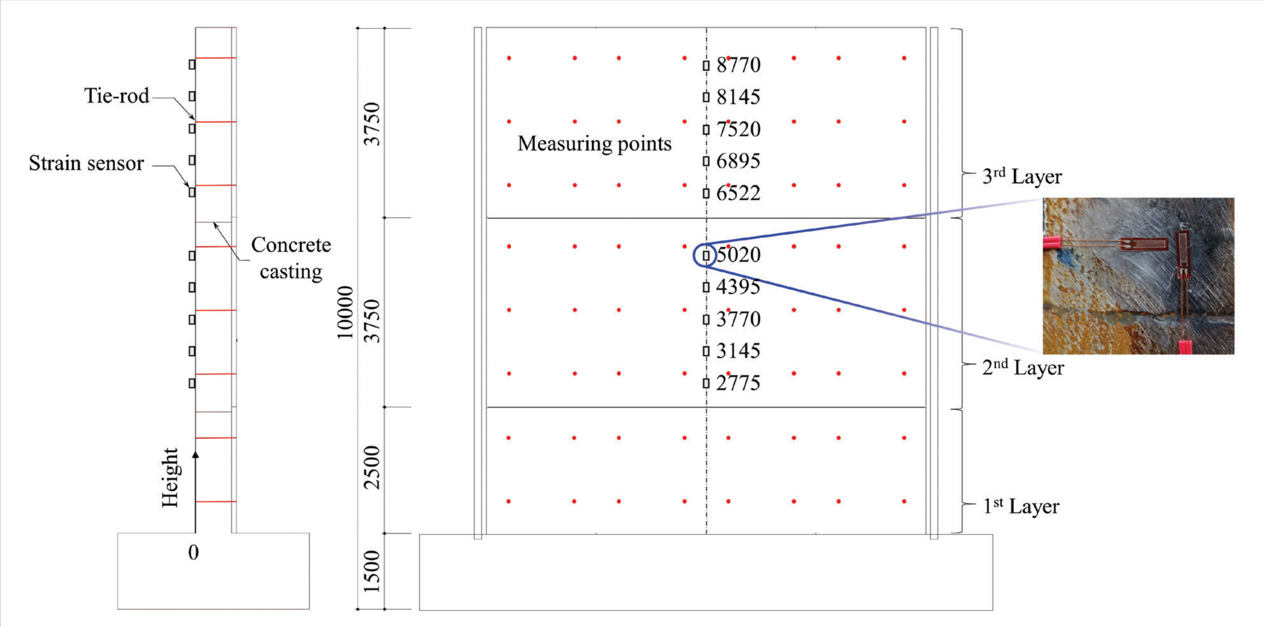


Figure 10. Strain sensors and measurement locations for the wall liner. Note: All strain sensor locations are listed in millimeters. 1 mm = 0.0394 in.

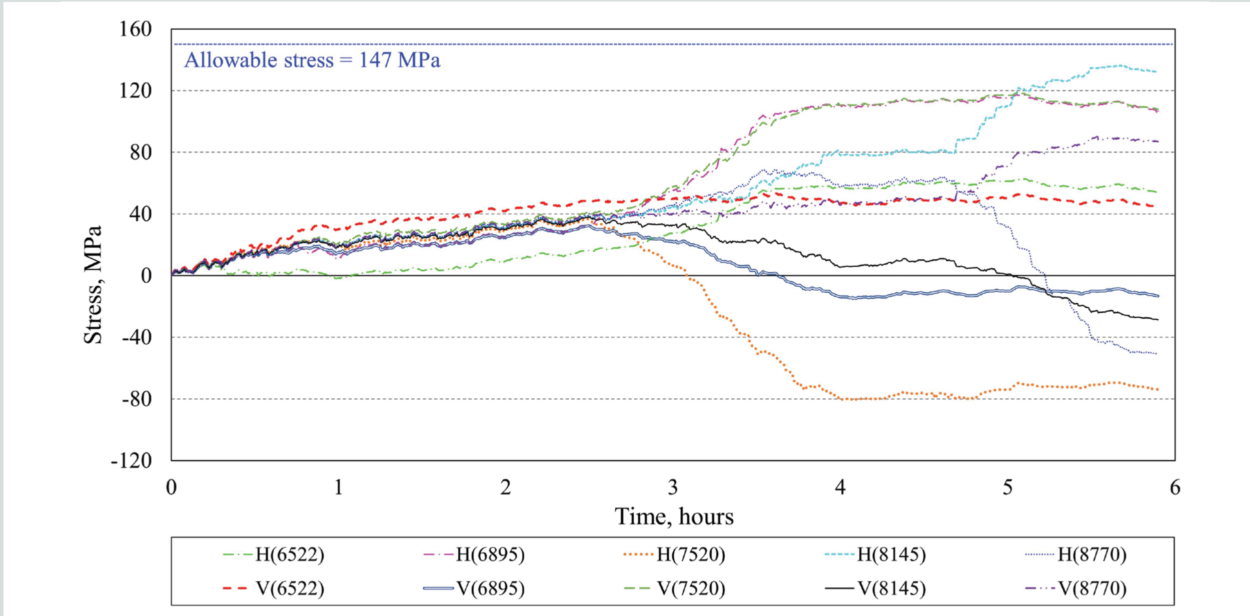


Figure 11. Stresses on the wall liner at panel layer 3 during concrete placement. Note: The numbers in parentheses describe the location of the stress above the base slab in millimeters. H = stress in the horizontal direction; V = stress in the vertical direction. 1 mm = 0.0394 in. 1 MPa = 0.145 ksi.

Strain measurement test method

Sensors were attached to the structure and connected to a data logger to collect the strain data and monitor the behavior of the wall liner during concrete placement. The locations of the strain sensors were selected based on the tie-rod positions, and the strain sensors were attached in the vertical and horizontal directions. **Figure 10** shows the locations of the strain sensors used for measurements.

Results of test measurements

Measurements for the wall liner were performed using strain sensors during concrete placement at panel layers 2 and 3, and the strain was measured from the beginning to the end of CIP concrete placement and curing. **Figure 11** shows the stresses in the wall liner at layer 3 where maximum stress occurred.

The test section wall liner was constructed using ASTM A516 414 MPa (60 ksi) steel plates, which are typically used for wall liner construction. To review the structural stability of the wall liner, the allowable stress was calculated as 147 MPa (21.3 ksi) according to the British Standards Institution's *Design and Manufacture of Site Built, Vertical, Cylindrical, Flat-Bottomed Steel Tanks for the Storage of Refrigerated, Liquefied Gases with Operating Temperatures between 0°C and –165°C, Part 2: Metallic Components.*[23] The maximum stresses on the wall liner in layers 2 and 3 were 132.2 and 108.0 MPa (19.2 and 15.7 ksi) in the horizontal and vertical directions, respectively. Therefore, it was verified that the test section was structurally sufficient for external forces, such as the form pressure of fresh CIP concrete.

Conclusion

The following conclusions were drawn from this study:

- The rapid construction method developed in this study uses a partial-thickness precast concrete panel and wall liner as a permanent form instead of the temporary forms used in the existing construction method. Accordingly, the construction process of the outer tank is improved by reducing construction time and eliminating the air raising process for the roof frame and the suspended deck. Because the wall liner is self-standing on the inside of the outer tank wall, it is expected that the inner and outer tank can be constructed simultaneously, thereby reducing the overall construction time by approximately six months.

- Unlike the existing construction technique, the proposed construction method does not require the dismantling of the temporary forms, which can allow construction to proceed without waiting for the concrete to cure fully because the precast concrete panels support the outer wall structure. In addition, unlike other methods using precast concrete that were considered, the proposed method has the advantage of relatively light panel weight, which makes the lifting and unloading of the panels using cranes easier.

- The test section construction process showed that the proposed construction procedure facilitated (and did not complicate) the assembly of reinforcing bars and placement of concrete. In addition, the constructibility was verified with regard to various anticipated concerns discussed previously, including the safe construction of panels and panel connections during concrete placement. Meanwhile, the strain measurements confirmed that stresses acting on the wall liner were less than the allowable stress.

Although fabricating the precast concrete panels is an additional step in the proposed construction method, the material costs are expected to be similar to those of existing construction methods because no installation or dismantling of temporary forms is required. Furthermore, the overhead costs are expected to be reduced because the construction time is shorter. Overall, the construction cost of the new method is expected to be the same as that of the existing construction method. In conclusion, the proposed method of construction for LNG storage tanks using partial-thickness precast concrete panels could drastically reduce the construction time without any significant economic impact compared with the existing method. In addition, it is expected that the proposed method is widely applicable to LNG storage tanks regardless of storage tank capacity.

Acknowledgments

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Notation

C_c = chemistry coefficient

C_w = density coefficient

E = elastic modulus

g = gravitational acceleration

h = height of fresh concrete

k = parameter for the stress state of the shell

L = length of circular cylinder

P = lateral pressure of fresh concrete

P_{cr} = buckling load

r = radius of curvature

R_p = rate of placement

t = thickness of circular cylinder

T_c = temperature of concrete

Z = parameter for the dimensions of the shell

κ = buckling coefficient

ν = Poisson's ratio for material

ρ = density of concrete

σ_{cr} = buckling stress

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Abstract

The concrete structure for liquefied natural gas (LNG) storage tanks is relatively simple but has a complicated construction procedure and takes a long time to construct. Also, because the inner tank cannot be constructed until the outer tank is finished, there are limitations to the current construction method in reducing the construction time. Therefore, a rapid method for LNG storage tank construction using precast concrete panels is proposed in this study to help shorten the construction time and improve quality control. The proposed method involves a change in the construction procedure. The precast concrete panels are used as the outer permanent form, and the wall liner is used as the inner permanent form for the outer tank wall. This is a new construction process that does not require installing and dismantling temporary forms. As a result, the inner and outer tanks can be simultaneously constructed once the self-standing wall liner is completed.

Keywords

Liquified natural gas, LNG, panel, rapid construction, storage tank, wall liner.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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