Design Method of Steel Liner on Inner Surface of PC Cylindrical Vessel for PC LNG Storage Tank

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ABSTRACT

This paper describes the results of investigation on the design method of steel liner for "Prestressed Concrete (PC) LNG storage tank”. This research was conducted by the committee which was organized by the Center for Promotion of Natural Gas in Japan. The steel liner is installed on the inner surface of the PC guard dike. Its functional requirements and the design concept were compared with those of the liner for PCG for nuclear power plants. A new design method was proposed that would allow the liner buckling caused by compressive deformation of the concrete body. Furthermore, these results were adopted in the draft for technical guideline of PC LNG storage tank.

1 INTRODUCTION

In recent years, LNG (liquefied natural gas) is increasingly being used for city gas in Japan. Many LNG terminals in regional cities are closely located to urban districts or confined to limited plotage. In order to meet the requirements of such an environmental situation, a certain type of storage tank, which is able to use such limited lots effectively and that satisfy the requirements of safety and economical efficiency, is in demand. In answer to such a demand, an integrated LNG above-ground storage tank comprising a conventional above-ground storage tank and an integrally joined prestressed concrete (PC) guard dike (hereinafter referred to as a PC LNG storage tank) is thought to be effective.

In order to formulate technical guidelines on safety and reliability of PC LNG storage tanks through experiment and analysis, the Center for Promotion of Natural Gas (CPNG), commissioned by the Ministry of International Trade and Industry (MITI) of Japan, has organized the Committee on Technical Development and Investigations for prestressed concrete LNG storage tanks from 1988 to 1990. The committee is composed of researchers and engineers from universities, gas companies and tank fabricators in Japan.

This committee has clarified the design concept of PC LNG storage tanks, investigated and studied the characteristic items of the PC LNG storage tank which are different from the conventional metallic double-wall cylindrical LNG above-ground storage tanks and have formulated comprehensive technical guidelines for planning, designing, construction and maintenance of PC LNG storage tanks [1].

One of the essential items to be studied was the design method of the lateral liner for the outer tank which is fitted to the inner surface of the prestressed concrete cylindrical guard dike. The outer tank liner is a structure member for holding N2 gas in the insulation layers during normal operation. If steel plates are employed for the outer tank lateral liner, the liner (hereinafter referred to as the steel-liner) may buckle by compressive deformation of the concrete following the introduction of SMiRT 11 Transactions Vol. H (August 1991) Tokyo, Japan, © 1991

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the prestress as the steel-liner is fitted on the concrete guard dike with anchors.

In order to find criteria for selecting structural specifications of the steel-liner and anchor, the design method for a liner for prestressed concrete containment vessels (PCCV) applied to nuclear power plants was referred to. Furthermore, an analytic investigation was made by utilizing multiple anchor models in which local deformation at the anchor fitting points was taken into consideration. Such local deformation is normally caused by unbalanced forces created by the buckling of the steel-liner. The findings are described in the following.

2 STRUCTURE AND DESIGN CONCEPT OF PC LNG STORAGE TANKS

An overall conceptual drawing of the PC LNG storage tank for investigation is shown in Fig. 1. The self-supporting cylindrical metallic inner tank, which stores LNG refrigerated at about -162°C, has a flat bottom and a spherical roof. The lateral and the bottom sides of the outer tank are composed of liner plate and fitted to the inside of the PC guard dike and the concrete foundation respectively. The insulation layers between the inner and the outer tank are filled with a powdered insulator and N₂ gas.

The structure of the PC LNG storage tank is different from that of a conventional LNG above-ground storage tank in some aspects, as shown in Fig. 2. Based on these points of difference, the functional and structural requirements of the PC LNG storage tank during normal operation and after spillage are shown in Table 1. The outer tank liner retains N₂ gas and prevents the penetration of humidity. The present paper focuses on a metallic liner, a steel liner in particular.

3 LOADING CONDITIONS OF THE LINER AND THE DESIGN PHILOSOPHY

3.1 Potential loads on the liner

In order to join the steel-liner integrally with the concrete body, the steel-liner is supported by the concrete body through anchors. Thereby, the gas pressure between the inner and outer tanks as well as the insulator pressure during normal operation are supported by the concrete body, and therefore, such mechanical loads can be disregarded as design loads of steel-liners and anchors. According to the results of a conceptual design of a storage tank with a capacity of several thousands to hundreds thousand m³, the compressive strain in the inner surface of the concrete body, which is calculated as being generated by the deformation of the concrete body due to the introduction of prestress, creep and drying shrinkage of concrete will amount to 200-600×10⁻⁶ strain and should be taken into account when designing the steel-liner.

According to the analysis, the strain generated by the seismic load, wind load, etc. are found to be in the order of 10⁻⁶ and can be disregarded.

Therefore, when designing a steel-liner, the loads to be taken into consideration are the ones induced by deformation of concrete caused by the introduction of prestress, creep, and drying shrinkage of concrete. The structure of the steel-liner and anchors should be able to follow such a deformation and, at the same time, should be able to retain N₂ gas.

3.2 Design philosophy of steel-liner

It is considered that the design method of the liner employed for the prestressed concrete containment vessel (PCCV) for nuclear power plants [2] can provide useful information. Therefore, the design methods for the above liner are compared with that for the liner of the PC LNG storage tank.

The requirements for the liner of PCCV is to prevent a leakage of the radioactive substance during normal operation and in extreme or abnormal conditions. Therefore, the liner is an important barrier for safety. However, the requirement for the liner of PC LNG storage tanks is to retain N₂ gas and to prevent the penetration of humidity in normal operation. And its importance for safety is considered a secondary matter.
Load cases of the PCCV are classified in detail according to the conditions at normal operation and in extreme or abnormal conditions. Allowable values are given for the corresponding load. The allowable strain for the liner of PCCV is the yield strain and the allowable displacement for anchors is 1/4 or 1/2 of the displacement at ultimate load. Accordingly, if the differences of functional requirements and importance between the PCCV and PC LNG storage tanks are taken into account, it is natural that the allowable design values of the liner for PC LNG storage tanks can be less severe than those for the PCCV.

In the designing guidelines for the PCCV, buckling of the liner is allowable against compressive force, such as the displacement limited load acting on the liner in normal operation. As in the case for PC LNG storage tanks, major loads acting on the liner are a displacement limited load, so the philosophy of allowing buckling is adoptable.

4 ANALYSIS AND DESIGN OF LINER-ANCHOR SYSTEM

4.1 Analysis of liner-anchor system [3]

Although buckling of the liner is permissible, not all the liners buckle simultaneously. Strain concentrates on the liner that buckled first, the anchor adjacent to it displaces to a large extent, and rupture of the anchor can be expected. This behavior can be analyzed by the model consisting of the liner-anchor system with a bent plate (Fig.3). The bent plate and anchors are idealized as non-linear springs and ideally flat liners as linear springs. Considering the equilibrium at each anchor point, non-linear simultaneous equations are obtained [4]. They can be analyzed by the iterative method.

In an actual liner-anchor system, even a flat liner will buckle if its compressive stress exceeds a certain value, so some of the liners would have already been buckled. In the following, bent plates are assumed to exist at a certain spacing, and the compressive stress of flat liners are calculated. It is also assumed that the flat liner buckles if the calculated value exceeds 1.5 \( \sigma_{st} \) (\( \sigma_{st} \) : Euler buckling stress), and the unbalanced force caused by the stiffness difference between the bent plate and the flat liner is released. This implies that the anchor experiences the severest condition when the compressive stress of the flat liner reaches 1.5 \( \sigma_{st} \). The maximum displacement of anchor \( \delta_n \) is determined for this condition.

The calculation are performed for the thickness of liner (t) : 3.2, 4.5 and 6.0mm, varying the anchor spacing (L) and the diameter of studs (d). The compressive strain of concrete body is assumed to be 6x10^-4. The maximum anchor displacement \( \delta_n \) are shown in Fig. 4.

4.2 Analysis of liner

In order to investigate the surface strain of the buckled liner, stress analyses are carried out on the liner with initial imperfection under prescribed displacement. Elastic-plastic analyses with geometrical non-linearity are performed using general purpose finite element program MARC.

The analyses are made on plates with thickness t of 3.2, 4.5 and 6.0mm by varying the length (L) from 250 to 1,000mm. One-half of the section is modeled by the two dimensional beam element taking into account of the geometric symmetry. The initial imperfection is approximated to a cosine curve and is calculated by taking its amplitude as t/4. The stress-strain relation of the mild steel (JIS SS41) was employed for the analyses. The compressive prescribed displacement divided by the length is defined to be the normal membrane strain \( \epsilon_{nm} \). The relationship between \( \epsilon_{nm} \) and the surface strain \( \epsilon_s \) is shown in Fig.5, where compression is taken as positive.

4.3 Design method of liner and anchors

The thickness of liners is normally determined by their workability and economical efficiency. A method is presented for determining the required diameter of stud at—
chords and fitting spacing of them with a view of preventing the rupture of anchors and liners.

(1) Required diameter of stud anchors
If the anchor displacement increases, the possibility for the anchor rupture will be greater. Therefore, a required minimum diameter should be determined for studs. The allowable anchor displacement is determined to be \( 0.5 \cdot \delta_u \) (\( \delta_u \): the anchor displacement at the ultimate load). The allowable displacement, determined from the load-displacement relations of anchors, is shown in Fig. 4. The intersecting points of this curve and the anchor displacement curve is the required diameter of studs. The displacement of the anchor has a maximum value at a certain anchor spacing (Fig. 4). Likewise, the required stud diameter also has a maximum value. The maximum values versus respective thickness are as follows:

<table>
<thead>
<tr>
<th>Plate thickness</th>
<th>Required stud diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2mm</td>
<td>7.8mm</td>
</tr>
<tr>
<td>4.5mm</td>
<td>10.1mm</td>
</tr>
<tr>
<td>6.0mm</td>
<td>12.3mm</td>
</tr>
</tbody>
</table>

(2) Anchor spacing
The relationship between the anchor spacing and the surface strain of the liner (Fig. 6) is obtained using the anchor spacing - the nominal membrane strain relation (Fig. 4) and the nominal membrane strain - the surface strain of the liner relation (Fig. 5). In order to prevent rupture of the liner, the surface strain of the liner should be kept below a certain value. The starting strain 0.03 of strain-hardening is adopted as the allowable strain of the liner. From Fig. 6, the lower limit values of the anchor spacing at the allowable strain 0.03 are as follows:

<table>
<thead>
<tr>
<th>Plate thickness</th>
<th>Anchor spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2mm</td>
<td>200mm</td>
</tr>
<tr>
<td>4.5mm</td>
<td>300mm</td>
</tr>
<tr>
<td>6.0mm</td>
<td>450mm</td>
</tr>
</tbody>
</table>

4.4 Summary of analyses
From the above mentioned analyses, if the strain of the concrete body is \( 600 \times 10^{-6} \), the stud diameter versus the liner thickness is as shown in Table 2. The lower limit values of anchor spacing are obtained to prevent the excessive surface strain, but buckling is prevented when the spacing is set narrower, so it is not required to set the lower limit values.

5 PRESCRIPTIONS OF THE DRAFTED TECHNICAL GUIDELINES

Based on the above mentioned analyses, a simplified design method, as described below, was prescribed in the drafted technical guidelines:

In case the concrete strain of PC guard dikes is less than about \( 500 \times 10^{-6} \), the soundness of outer tank liners can be ensured without making a design calculation, provided the following conditions are satisfied.

(1) In case of stud anchors, set the stud diameter to be more than 2.5 times the thickness of the liner and make the anchor spacing less than 1,000mm by taking the workability of storage tanks into consideration.

(2) In case of line anchors, set the thickness of the shape steel web to be thicker than that of the liner and make the vertical anchor spacing less than 1,000mm taking the workability of storage tanks into consideration. In case that the line anchors are arranged vertically, buckling deformation of the liners is controlled in between the line anchors, therefore, an arrangement in vertical direction only will be enough.
6 CONCLUSION

The design concept for the PC LNG storage tanks was clarified and the technical guidelines were drafted by the Committee on Technical Development and Investigation for Prestressed Concrete LNG Storage Tanks. The Committee investigated the design method of the outer tank lateral liners (steel-liners) to be installed on the inner surface of PC cylindrical guard dike for LNG storage tanks by referring to the design method of PCGY, which has structural similarities with the PC LNG storage tanks. The results of the investigation are as follows:

(1) The functions of the liner and loads to be taken into consideration were clarified. A new design method was proposed that would allow the liner buckling, caused by compressive deformation of the concrete body.

(2) A simplified design method for steel liners was prescribed in a technical guideline draft for PC LNG storage tanks. The technical guidelines stipulated the required cross section dimension of anchors and the anchor spacing for stud anchors and line anchors, when the PC guard dike's concrete strain is under about 600×10⁻⁶.

We wish to express our thanks to the Ministry of International Trade and Industry and city gas companies for their kind cooperation in carrying out this investigation.

REFERENCES


Table 1. Design concept of PC LNG storage tanks

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>STRUCTURE</th>
<th>FUNCTIONAL REQUIREMENT AS A CONTAINER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Tank</td>
<td>Cylindrical tank with metallic flat bottom</td>
<td>Liquid-tight and gas-tight</td>
</tr>
<tr>
<td>Outer Tank</td>
<td>Shell and bottom: metal or non-metal liner</td>
<td>Retaining N₂ gas and preventing penetration of humidity</td>
</tr>
<tr>
<td>Guard Dike</td>
<td>Prestressed concrete</td>
<td>Retaining liquid</td>
</tr>
<tr>
<td>Foundation</td>
<td>Reinforced concrete</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

Note: Functional requirement of structural aspect is omitted. N.A.: Not Applicable

Table 2. Stud diameter versus liner thickness

<table>
<thead>
<tr>
<th>Liner Thickness (mm)</th>
<th>Diameter of Stud Anchor (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>More than 2.5</td>
</tr>
<tr>
<td>4.5</td>
<td>More than 2.3</td>
</tr>
<tr>
<td>6.0</td>
<td>More than 2.1</td>
</tr>
</tbody>
</table>

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Fig. 1 Overall Conceptual drawing of PC LNG Storage Tank

Fig. 2 LNG Above-ground Storage Tank

Fig. 3 Liner anchor system

Fig. 4 Anchor displacement versus diameter of stud

Fig. 5 Surface strain versus nominal membrane strain in liner

Fig. 6 Surface strain of liner versus anchor spacing