Ductility of Prestressed Concrete at Extremely Low Temperature for PC-LNG-Aboveground Storage Tank

H. SHIBATA, H. OKAMURA
University of Tokyo, Tokyo, Japan
T. TAKAGI
The Center for Promotion of Natural Gas, Tokyo, Japan
K. UKAJI, H. ITO, H. OUCHI
Obayashi Corporation, Tokyo, Japan

ABSTRACT

The material and structural ductility of prestressed concrete at extremely low temperature is investigated, and the findings of the study insure a safe engineering practice of PCLNG tank. A draft of the engineering guideline for PCLNG tank is developed.

1 INTRODUCTION

LNG, liquefied natural gas, is one of the most important energy sources for Japan. The storage and operation of LNG require a particular attention to LNG's extremely low temperature, -164°C. For the natural gas supply in local cities by small gas companies, a new concept of LNG storage, PCLNG tank, is introduced and studied by MITI. The Committee on Technical Investigation of PCLNG Tank is formed at The Center for Promotion of Natural Gas(CPNG) on behalf of MITI.

To insure the safety and reliability of PCLNG tank, the extensive and overall engineering studies on design, analysis, construction, quality control, material, operation, and safety, are carried out by the Committee. Among the study topics, a particular emphasis is given to the evaluation of structural ductility and provides solution for liquid-tightness for the proposed prestressed concrete tank. This paper deals with a new development in the ductility and provides solution for liquid-tightness problems at extremely low temperature down to -164°C, which are incorporated in the engineering guideline drafted by the committee(CPNG 1989, 1990).

2 CONCEPT OF PRESTRESSED CONCRETE LNG TANK

The PCLNG tank consists of an inner tank made of 9% nickel steel and an outer container made of prestressed concrete. The self-supporting inner tank holds -164°C liquid as a primary barrier and is protected by insulation layers that control heat transfer.

As shown in Figs. 1 & 2 the outer container is composed of a concrete base slab, a concrete side wall and a concrete or steel domed roof. The inner face of the concrete container is double-covered with a steel liner and a thin insulation layer. The liner should be gas tight to purge oxygen as well as moisture from the space of insulation structure. The insulation attached to the interior of the concrete container, moderates thermal shock or an extreme temperature gradient developing in the concrete in case of liquid spill. To protect the foundation from freezing, a heating system is utilized for the model of the concrete foundation.

The structural joint of the side wall and the bottom slab is required to be monolithic in order

SMiRT 11 Transactions Vol. H (August 1991) Tokyo, Japan, © 1991

to keep the joint liquid tight and aseismic. For the same reason the prestressing tendon of grouting type is selected to improve a liquid-tightness.

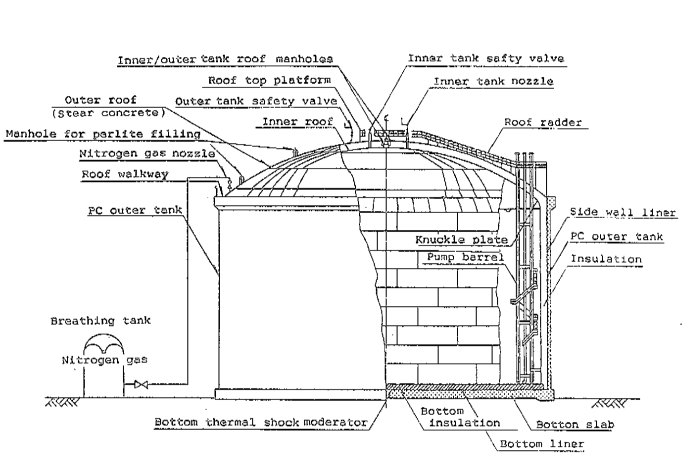

Fig.1 Concept of PCLNG Tank

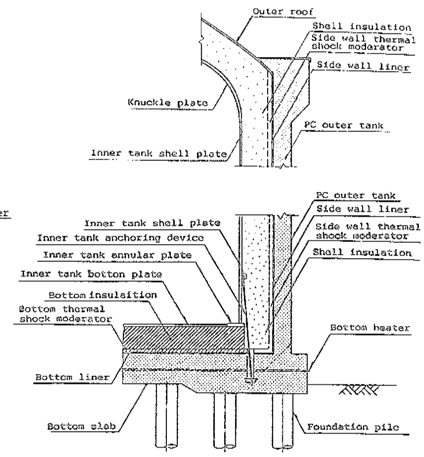

Fig.2 Details of PCLNG Tank

3 SAFETY REQUIREMENTS OF PRESTRESSED CONCRETE FOR LNG APPLICATION

As a secondary barrier of LNG storage system, the prestressed concrete(pc) container is required to hold liquefied natural gas for a certain period if the liquid spill accidentally occurs from the inner tank. On such extreme loading condition, the structural stability and performance of the pc container should be carefully examined to insure its reliability as a second barrier, i.e. material and structural ductility, and liquid-tightness of the pc structure against the spilled LNG.

The draft guideline adopts the limit state design method for concrete structure. The method defines the structural requirements of pc container. Most important and unique limit states to the design concept are as follows:

LIQUID-TIGHTNESS LIMIT(after liquid spill) ---- The reliability of pc structure as a container depends on the liquid-tightness of prestressed concrete structure. Due to lack of rational criteria to evaluate the structural behavior of pc structure, it is essential to carry out a relevant experimental and analytical study on the structural damage caused by concrete cracks on the occasion of LNG spill. Based on such engineering findings, the design guideline should be discussed.

ULTIMATE STRENGTH LIMIT(structural failure) --- Safety of the concrete structure against the structural failure observed in loading conditions under earthquake,storm,pressure- and hydraulic-tests and liquid spill should be confirmed. Since low temperature like that of LNG tends to cause materials brittle, the strength as well as deformability of materials and structural members of the outer tank particularly strain level beyond the yielding should be carefully examined.

4 DUCTILITY OF PRESTRESSING BAR AND STRAND

The mechanical properties, in terms of elongation and reduction of cross-sectional area at necking, of prestressing bar and strand are summarized in Figs. 3 & 4, which are obtained from tensile tests to failure. The failure mode of the strand specimen is ductile even at -164°C, while the failure of bar specimen tends to be brittle as temperature lowers beyond -100°C. The elongations of both specimen show similar results that the prestressing bar may be able to apply to a design temperature not lower than -100°C.

To investigate a V-notch effect on the prestressing strand for use in cryogenics condition, further tensile tests are performed using notched king wires of 15.2mm 7-wire strand . As shown in Fig.5 (Rai et.al. 1990), if the notch depth due to the wedge action does not exceed 0.5mm, the strand behaves to be ductile. Those test results assure that the strand is ductile till -164°C.

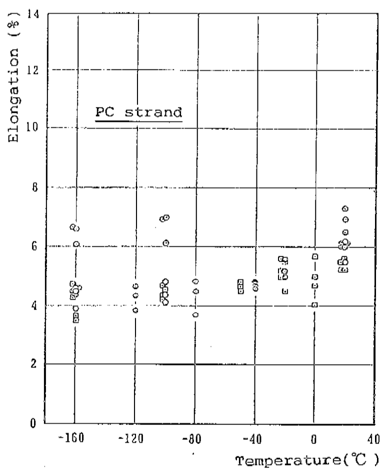

Fig.3 Elongation of PC Strand

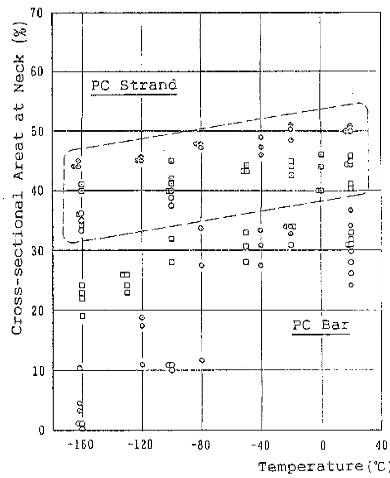

Fig.4 Reduction of Necking Area

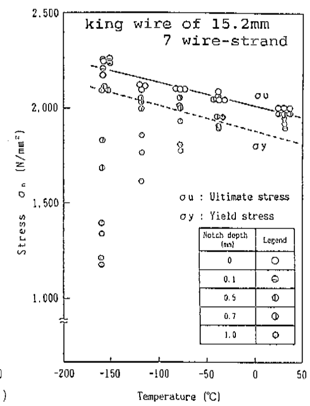

Fig.5 V-Notch Effect

5 DUCTILITY OF PRESTRESSING ANCHORAGE

The anchorage assembly of typical multi-strand tendon consists of wedges, an anchorage block and a guide block. The anchorage block uses to experience most severe stress conditions, such as a combination of flexural tensile stress and shear stress. In order to keep overall structure safe under extreme loading conditions with exceptional low temperature, the anchorage shall be designed stable up to the ultimate strength of the structure.

The specimen taken from the three types of anchorage systems are tested by using Charpy impact method. Results are shown in Fig. 6. It must be noted that the blocks are made of alloy steel containing a certain percentage of nickel, instead of carbon steel used for standard engineering practice.

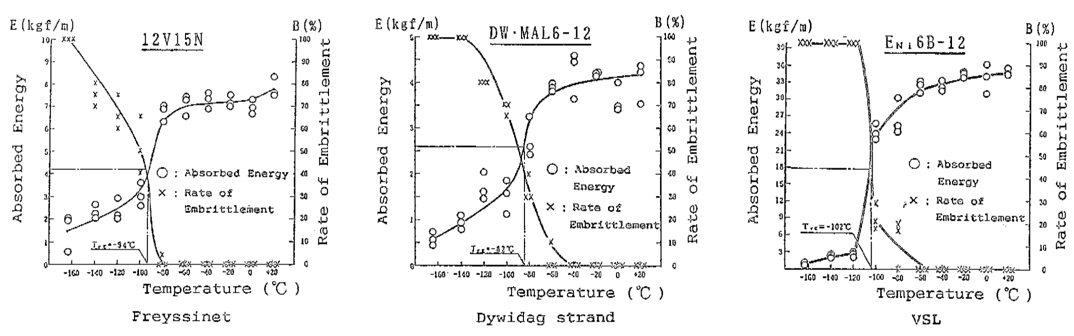

Fig.6 Transition Temperature of Anchorage Block Specimen

The test results are evaluated to determine the applicable design temperature as the criteria. The energy absorption should be larger than 48Nm. The rate of brittle failure should be less than 50%, and the lateral expansion should be larger than 0.381mm in case that specimen size is 10mmx8mm. The transition temperatures of the anchorage specimen are -82°C for highest and -102°C for lowest. The design temperature of anchorage for PCLNG tank design should be within the temperature limits obtained from these tests.

6 DUCTILITY EVALUATION OF TENDON-ANCHORAGE SYSTEM

6.1 Evaluation Method

The assembly of pc strands and anchorages at a design low temperature should be able to retain up to the ultimate prestressing force with large elongation. Any brittle failure and undesirable deformation should not be generated in the anchorage. ASME and FIP provide the codes to evaluate the performance of tendon-anchorage system at normal temperature. The results of literature survey indicate that a good engineering practice with extensive quality assurance program well meets those existing codes.

For the use of pc assembly at low temperature such as LNG storages, few research and/or experimental works are available, particularly in full scale model tests such as 12T15. However, an evaluation method of the tendon-anchorage system has been proposed by FIP(FIP 1982,Rostasy 1986). The Committee adopted as follows:

LOADING --- The overall assembly installed in a refrigerated testing equipment is loaded by means of prestressing force equivalent to 0.9 of yield strength. Keeping the tensile force constant, the system is cooled down to a testing temperature and loaded ten cycles of additional tensile load in the range of the yield and 0.9 of yield strength. Finally, the load increases on the tendon system until its failure(Fig.7).

STRENGTH --- The ultimate strength of the tendon-anchorage system should exceed the low temperature yield strength of tendon. The rate of anchorage efficiency is given by the ratio of the system's ultimate strength to the tendon's yield strength.

ELONGATION --- The system and anchorage should not fail or slip before the elongation of the tendon system exceeds the sum of 2% and an elongation due to the allowable design prestressing load.

The testing program of the full scale tendon-anchorage system is carried out on three types of anchorage,namely,Freyssinet,Dywidag and VSL.

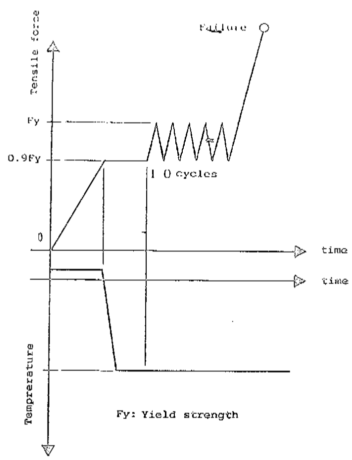

Fig.7 Loading and Cooling Procedure

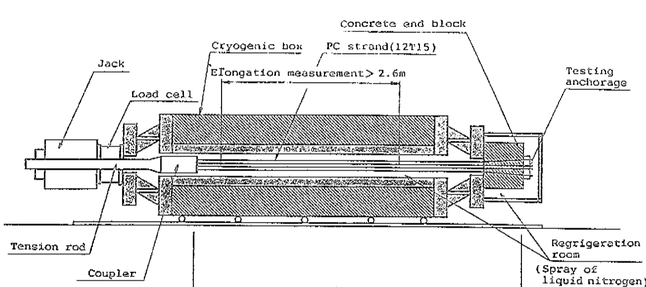

Fig.8 Illustration of Testing Apparatus

6.2 Testing Program

The tendon is 12 strands of 15.2mm(type B of JIS). Product classifications of each type are 12V15N(Freyssinet), DW·MAL6-12(Dywidag) and ENi6B-12(VSL).

Testing temperatures are room, -100°C and -164°C. The number of specimen are three for each temperature. The testing apparatus is specifically designed for this program. The temperature is controlled by spraying of liquid nitrogen (Fig.8). Since the temperature variation along the specimen causes a strength irregularity along the strands, the temperature distribution is carefully monitored and controlled.

The anchorage is installed one end of the tendon,while another end is fixed by a coupler with white metal fill. The loading and cooling procedures are illustrated in Fig. 7.

6.3 Low Temperature Ductility of Tendon-Anchorage System

Experimental results given in Table 1 indicate that the ratio of anchorage efficiency and the ultimate strength of the system to the yield strength of the strand reaches and exceeds 1.00, which conform to the evaluation criteria. The efficiency ratios are 1.01-1.04 at -100°C and 1.00-1.04 at -164°C. The elongations of the system specimen at failure are 2.7-4.2% at -100°C and 2.9-4.0% at -164°C. An example of strain-tensile force relationship given in Fig. 9 shows the tendon-anchorage system exhibits satisfactory plastic strain beyond the yield.

Table 1 Anchorage Efficiency Ratio & Elongation

	Type	Strand	Testing temperature (℃)	Testing results (three specimen) Anchorage Efficiency	Testing results (three specimen) Ultimate Strain (%)
Freyssinet	12V15N	PC strand 12 strands of 7-wire 15.2mm (Type B of JIS)	room -100 -164	0.97～1.00 1.01～1.05 1.01～1.03	2.6～3.7 2.7～3.7 3.3～3.6
Dywidag strand	DW·MAL6-12		room -100 -164	0.99～1.02 1.03～1.04 1.02～1.04	3.6～4.5 2.8～3.5 2.9～4.0
VSL	E_{Ni}6B-12		room -100 -164	1.01～1.03 1.05 1.00～1.01	3.8～4.6 3.6～4.2 3.0～3.3

Note

Temp.	Anchorage Efficiency	Ultimate Strain
Ambient	$\eta_A = \dfrac{\text{strength of tendon-anchorage assembly } F_{TU}}{\text{nominal strength of prestressing steel min } F_{CU}} \geqq 0.97$	$E_U \geqq 2.3\%$
Cryogenic	$\eta_A = \dfrac{\text{strength of tendon-anchorage assembly system } F_{TU}}{\text{yield stress of prestressing steel at test temperature } F_{YO}} \geqq 1.00$	$E_{UO} \geqq E_{PO}+2\% \fallingdotseq 2.67\%$(CEB-FIP) the measured total strain larger than the yield strain of prestressing steel sttest temperature

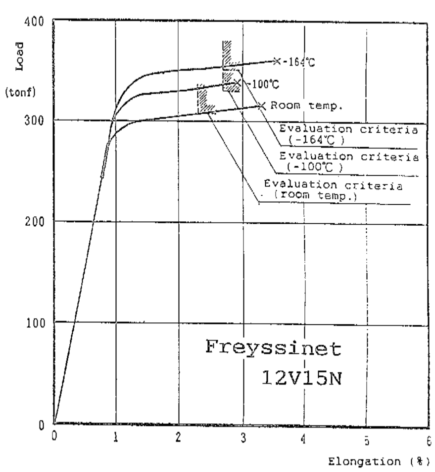

Fig.9 Strain-Force Relationship

The failure mode of each specimen is inspected by analyzing the development of necking. All specimen well develop necking, and no brittle failure surface is noticed. The ductility requirements described above seem to be practical as an engineering guideline.

Strand failure due to tensile force locates on a particular point, 25-60cm away from nearest face of the wedge. The distance varies with shape of each anchorage type. As long as a wedge type anchorage is concerned, it is unavoidable to create a point of bending on the tendon strand, because a duct dimension is changed from the sheath to the anchorage block.

7 DUCTILITY AND LIQUID-TIGHTNESS OF PC STRUCTURAL MEMBER

7.1 Low Temperature Ductility of PC Structural Member

To investigate the performance of prestressed structure under strain propagation with high velocity such as the strain induced by earthquake, the impact loading tests on a prestressed beam has been carried out(Rai et.al. 1990). The testing temperatures are as low as -60, -120 and -164°C. This experimental study reveals the structural behavior of pc beams under the impact loading. The ultimate load bearing capacity of beam, either of static or impact, remarkably increases when the testing temperature is lowered.

When the temperature decreases, the energy absorption of the impact loading tends to decreases compared to the static loading. However, the beam at -164°C under the strain velocity of 100cm/sec still retains 70% of the ductility exhibited at the static loading.

Assuming the loading speed to be 100cm/sec equivalent to the strain speed due to earthquake loading, the pc structure refrigerated to -164°C certainly behaves to be a ductile structure.

7.2 Liquid-Tightness of PC Structural Member

In case of the liquid spill from the inner tank, the pc outer containment should retain LNG spilled. An experimental and analytical research conducted by Maekawa et.al. 1991, specifies relationship between initial crack width and rate of gas/liquid flow. After obtaining time history of leakage phenomena, the analytical model is developed, and the numerical simulation follows up the experiment.

The research concludes that if the initial crack of concrete structure is narrower than 0.1mm, no liquid penetrates the crack developed through the structure. Even the crack width is as wide as 0.2mm at the liquid side, no leakage occurs if the other side crack is close to nearly 0mm. Because the analytical model developed in that research simulates the leakage phenomenon through a concrete cracking, the liquid-tightness of a particular concrete structure can be analyzed by computer codes(Maekawa et.al.1991).

Taking into account those findings, the guideline requires the engineering practice either the concrete structure should keep a residual compression zone larger than 10cm or, if the maximum tensile stress of rebar does not exceed 1000kgf/cm^2, a compression zone may be reduced to one tenth of the concrete thickness. The guideline also specifies to provide counter measures for the prevention of thermal cracking during construction of the PCLNG tank.

8 CONCLUSIONS AND ACKNOWLEDGEMENT

The material and structural ductility as well as the liquid- tightness is thoroughly studied by the committee, and the findings are incorporated in the draft of engineering guideline for prestressed concrete LNG tank.

The authors express acknowledgement to the Ministry of International Trade and Industry and sincere thanks to the Committee members for their active contribution to this investigation.

REFERENCES

Center for Promotion of Natural Gas (1989, 1990), The Report on Technical Development and Investigations for Prestressed Concrete LNG Storage Tanks(in Japanese)

Rostasy,F.S. (1986), Prestressing Steels and Systems for Storage Tank for Refrigerated Liquefied Gases, 10th FIP Congress

Rai,C.,Kitamura,H.,Ukaji,K. (1990), Behaviour of Prestressed Concrete Containment Structure Under Extremely Low Temperature, Concrete Library of JSCE No. 14

Maekawa,K.,Hasegawa,H.,Kurosaka,T.,Asai,K.,Kitamura,H. (1991), Gas-Liquid Two Phase Flow Through A Crack in Concrete, East Asian Conference on Structural Eng. & Construction