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BEHAVIOUR OF PRESTRESSED CONCRETE CONTAINMENT STRUCTURE UNDER EXTREMELY LOW TEMPERATURE

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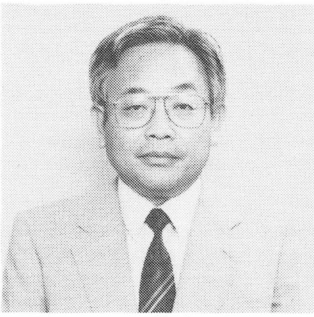

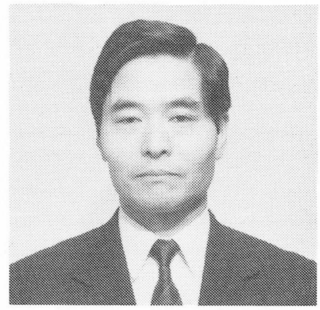

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SYNOPSIS

Prestressed concrete has been recognized as a suitable containment structure to store a refrigerated liquefied gas such as LNG(-164℃). This paper reports the experimental study which assess the mechanical properties at low temperature of prestressing steel, prestressing tendon systems (tendon-anchorage assembly), and prestressed concrete beams. The ductility and liquid-tightness of those materials and structures are evaluated with emphasis on the experimental works consist of five phases; (1)the testing and evaluation of notch sensitivity of prestressing wire, (2)the examination of ductility of anchorage materials, (3)the static and cyclic tensile tests at low temperature of 12-strands tendon systems, (4)the impact loading test at low temperature of prestressed concrete beams, and (5)the performance of the beams under direct contact of a liquefied nitrogen(-196 ℃). The study revealed that prestressed concrete and steel materials with a proper material specification are suitable for a cryogenic storage structure.

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1 . FOREWORD

The growing demand of liquefied natural gas (LNG, -164℃) in Japan has reqired to construct a number of cryogenic containment storages. On the engineering practice rather strict safety requirements have been imposed on the design and construction of containers for the refrigerated flamable gas, which volume is condensed in one 600th by liquidizing. From the design points of view, in particular, the storage structure should satisfy the requirements on the safety of container and structural materials, such as material behaviours toward sufficient ductility in low temperature.

The first application of prestressed concrete for cryogenic products was to store liquefied oxygen in 1952. Since then 26 containers for LNG have been constructed. While various studies on the behaviours of prestressed concrete at low temperature has been done by many researchers, there are few internationally established testing method as same as safety criteria for ductility requirements ,except the FIP recommendations[1] on the assessment of performance of tendon-anchorage assembly.

This paper deals with the experimental investigations of a behaviour of each of prestressing assemblies and the prestressed concrete under various temperatures from the ambient to -164℃. The test results demonstrate the acceptability of the prestressed concrete structures as a cryogenic storage tank for LNG or any other cryogenic products.

2. SAFETY REQUIREMENTS, TESTING METHODS AND EVALUATION CRITERIA FOR PRESTRESSED CONCRETE TANKS AT LOW TEMPERATURE

2.1 Structures of Prestressed Concrete Storage Systems

The prestressed concrete tanks for cryogenic use operating in Europe and U.S.A. are classified into the following two types[2] as shown in Fig.1 .

SINGLE CONTAINMENT
Prestressed concrete tank used as a primary barrier (in contact with the cold liquid). The prestressed concrete tank with a liquid/vapour tight membrane is designed to support the membrane and the liquid pressure, and in an event of the membrane failure, to resist various loads induced by the failure.

DOUBLE CONTAINMENT
Prestressed concrete tank used as a secondary barrier. This type of structure consists of a self-supporting primary container (made of steel i.e. 9%Ni) and a prestressed concrete secondary container resisting external loads. The concrete tank stores the cold liquid if the primary steel tank is in accidentally failed.

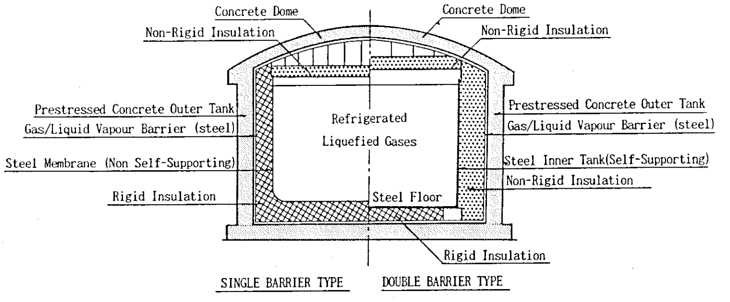


Fig.1 Typical Structural Arrangement of Prestressed Concrete Storage Tank for Refrigerated Liquefied Gas

2.2 Safety Requirements for Prestressed Concrete Tank

The safety criteria required to the cryogenic storage tanks should include the structural safety to prevent any liquid spillage against the static and dynamic loadings with low temperature acting from either of internal or external.

(1) Load Bearing Capacity
The structural resistance of the prestressed concrete against applied loads is able to evaluate by means of ultimate strength and deformability. Such structural capability should be assessed at broad temperature range down to -164℃. Furthermore the ductility of the prestressed concrete should be high enough to prevent a brittle mode of failure. The structural integrity should also be maintained in a case of direct contact of a cold liquid to the tank structure such as a thermal shock.

(2) Liquid-tightness
There are two design concepts for the liquid-tightness of prestressed concrete. One is that the liquid is kept by the prestressed concrete structure itself. Another relies the liquid-tightness on the combination of prestressed concrete and watertight materials, i.e. a membrane or a steel liner. This paper regards the former concept that the prestressed concrete wall is responsible to keep the refrigerated liquefied gas without any liquid spillage through the wall.

2.3 Methods to Evaluate Safety Requirements

Since the prestressed concrete is a composite structure consisting of prestressing steel, reinforcement, anchorage and concrete, the safety requirements should be evaluated on not only each structural material but also a prestressing tendon anchorage assembly and a prestressed concrete member. The evaluation items and testing methods employed herein are intended to cover fundamental still sufficient, structural engineering items, to assess the ductility of prestressed concrete structure at low temperature. These evaluation is applicable to not only cryogenic storage tanks but also many other structures subjected to extremely low temperatures. The lowest temperature taken in this study is -164 ℃, which is equivalent to LNG tempererature and the lowest in the current practice. Since the behaviour of reinforcement and concrete at LNG temperature are available for the operation and engineering practice[3] of existing in-ground LNG tanks, this paper emphasize on the low temperature behaviour of the prestressing steel, anchorage, tendon anchorage assembly and prestressed conctete beam. Table.1 summarizes the evaluation items,testing methods and evaluation criteria.

(1) Strength and Deformability at Low Temperature
The strength and deformability of the prestressed concrete is confirmed under the loading conditions which postulate imposed loads as well as performance of prestressed concrete tanks. Seven wire strands, a typical tendon used in a prestressed concrete, were tested up to ultimate tensile strength in a cold box to evaluate the tensile strength, elongation and mode of failure. The structural behaviour of the anchorage is evaluated in terms of strength, deformability and anchorage efficiency by the tension test of tendon anchorage assembly system, which conform to the FIP recommendation. The prestressed concrete beams are subjected to a point load at the span centre. The ultimate load, deflection, failure process as well as the mechanism of the beams are investigated.

(2) Resistance to Brittle Failure
The resistance against brittle failure of each prestressing material is examined by the following tests:

Table 1 List of Assessment Items, Test Methods and Evaluation Criteria for the Assessment of Structural Behaviours of Prestressed Concrete at Low Temperature (-164 ℃)

Structural material and member		Strength and Deformability				Liquid-tightness
		Strength property	Deformability	Ductility	Resistance to thermal shock	
Prestressing Strand	Assessment item	Tensile strength and yield strength	Ultimate strain	Tensile strength and yield strength	Stress, strain and no brittle failure	———
	Test method	Tensile test		Tensile test of a king wire with various notch depth	Thermal shock test of tendon-anchorage assembly	———
	Evaluation criteria	Not less than strength specified in JIS-code at all temperatures	Not less than strain specified in JIS-code (3.5%)	No low-stress failure at temperatures from room to -164℃	Strain induced less than yield strain, and no visible defect	———
Anchorage	Assessment item	Tensile stress at tendon failure	Strain at tendon failure	Absorbed energy, rate of embrittlement	Generated stress and strain, no brittle failure	———
	Test method	Tensile test of tendon-anchorage assembly		V-notch Charpy V-notch test	Thermal shock test of tendon-anchorage assembly	———
	Evaluation criteria	Safety margin to ultimate strength	Safety margine to ultimate strain	Transition temperature, lowest allowable temperature	Generated strain less than yield strain, no visible defect	———
Tendon-anchorage assembly	Assessment item	Tensile strength and yield strength	Ultimate strain	Ultimate strain, reduction of area, location of failure, surface condition	Behaviour of prestressing steel, strand and anchorage component	———
	Test method	Tensile test of tendon-anchorage assembly		Tensile test after cyclic yield loading	Thermal shock test of tendon-anchorage assembly	
	Evaluation criteria	Anchorage efficiency η=0.97 at room temperature η=1.00 at cryogenic temperature	Ultimate strain not less than 2.3* at ambient temperature Ultimate strain not less than yield+1* at cryogenic temperature	Ductile failure surface of prestressing strand, no unstable failure	Guarantee of soundness of tendon- anchorage assembly	———
P/C beam	Assessment item	Maximum load bearing capacity	Deformability, cracking	Failure mode, failure mechanism absorbed energy	Thermal stress, restoring moment	Limit state of spillage occurrence
	Test procedure	Flexure test of P/C-beam with point load		Flexure test of P/C-beam with impact load	Thermal shock test	Liquid-tightness test of P/C-beam with end-fixed develepment support
	Evaluation criteria	Not less than strength at room temperature	Sufficient deformability in post yield strength region	Sufficient of absorbed energy, no unstable failure	Neither spillage through crack nor unexpected behaviour structural un-stability	Limit state of crack at spill initiation

Test of Prestressing Steel

The V-notch test of prestressing steel aims to check the tensile strength and failure mode of a notched prestressing wire. The reasons of employing the V-notch test are:

- The prestressing steel is not necessary to assume welding.
- The loading is to be a pure tension and the effects of a flexure and shear are minimal.
- It does not face to a direct impact loading because of a protection with concrete grouting and re-bars.

Test of Anchorage

The V-notch Charpy impact test is carried out on the anchorage steel materials, specifically an anchorage component subject to flexure and tension loadings. The test evaluates the transition temperature of each anchorage material derived from the absorbed energy and the rate of brittle failure.

Test of Tendon Anchorage Assembly

The test method is conforming to the FIP recommendation of tendon anchorage assembly at low temperature, which impose the 10 cyclic loadings at yield stress level to assess a sensitivity to a latent damage in the assembly. The test data provides the ultimate strength, elongation at failure, and failure mode of the assembly.

Test of Prestressed Concrete Member Beam

The behaviour of the prestressed concrete beams under the impact loading with low temperature is examined in terms of the ultimate load, deflection, and energy absorption.

(3) Structural Integrity against Thermal Shock

The strain change of the prestressing strand and anchorage of the tendon anchorage system due to the thermal shock test is measured and evaluated. The thermal stress induced and the structural behaviour of prestressed concrete beam are investigated by applying a liquid nitrogen (-196℃) at the beam surface.

(4) Liquid-tightness

The prestressed concrete beam, which is a model of the tank wall, is subject to the test of liquid tightness in such a way that the axial tensile force is applied at the beam ends to develop transverse tension cracks combined with the steady state temperature gradient at the beam. The strain of a reinforcement at spillage was found from this test.

2.4 Safety Criteria

Besides the FIP recommendations, JIS (Japan), WES[7] (Japan) and ASTM[8] are also included for the structural safety requirements of prestressing materials and the evaluation criteria of the testing results. The structural safety criteria are established to meet the structural behaviour of strength, deformability, ductility, resistance to thermal shock and liquid-tightness.

Prestressing Wire

The strength and deformability at low temperatures should satisfy the requirements of JIS those of room temperatures. The integrity of the tendon anchorage system under the themal shock is required to be stable. The ductility of the steel is investigated by a V-notch tension test which demonstrates the toughness of notched wire section. The failure surface should be ductile and no low-stress failure at the stresses lower than the yield strength should occur.

Anchorage
The strength and deformability of a prestressing tendon system are evaluated by the anchorage efficiency. The ductility of anchorage materials are evaluated by the transition temperature derived from the Charpy impact test.

Prestressing Tendon Anchorage System
In accordance with the FIP recommendations, the ultimate strength, elongation at failure, anchorage efficiency and temperature dependency of those items are investigated for the 12-strands tendon anchorage assembly. No unstable failure or rupture should exist at any part of the assembly and the maximum elongation or strain of the tendon should not be less than those of yielding.

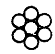
Prestressed Concrete Member Beam
The strength and deformation of prestressed concrete structure should be evaluated by the ultimate load carring capacity. Since the engineering practice of structural design is based on the structural strength at normal temperature, the minimum requirement on strength is that the structure in low temperature should be inferior to the strength at normal temperature. The structural deformation in the post-ultimate loading region of the structure at given test temperature down to -164℃ is also not less than the deformation expected in normal temperture. The structural ductility is evaluated by the energy absorption defined as the integration of the load-deflection curve. Both the structures in low and normal are desirable to exhibit the equivalent energy absorptions. The failure mode of the structure should not be brittle.

3. PROPERTIES OF PRESTRESSING STEEL IN LOW TEMPERATURE

3.1 Strength and Deformability Test for Prestressing Steel[4]

(1) Specimen
The specimen of tensile test are the 7 wire strand of 15.2^{mm} diameter. In order to avoid the anchorage effect on the test results, the both ends of the strand are anchored by the white metal casting. Table 2 shows the mechanical properties of the prestressing steel specimen and the code requirements of JIS. The test temperatures are the room,-20,-40,-80,-120 and -164 ℃ with the three specimens at each temperature.

Table 2 Mechanical Properties of Prestressing Steel

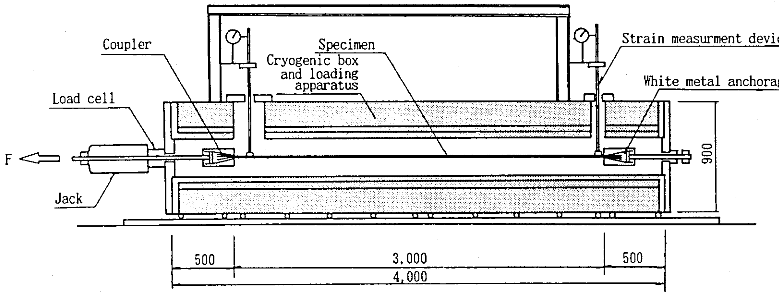
Steel	Designation	Symbol	Section	Nominal diameter	Cross section area	Unit weight
7 wire-strand class-B	15.2 ^{mm} 7 wire-strand	SWPR7B		15.2 ^{mm}	138.7 mm^2	10.1 N/m

Specification	Load at 0.2% proof stress (KN)	Tensile load (KN)	Elongation (%)	Relaxation (%)
JIS Code	min 226	min 266	min 3.5	max 3 (10^{hr})
Test result	256.5	276	6.2	0.54 (10^{hr})

Note : JIS=Japan Industrial Standard

(2) Testing Method

The test specimen of 3^m long with the effective distance 2.7^m is subject to a static tensile test until failure. The test apparatus is illustrated in Fig.2. Measurements are made on the strength, elongation and reduction of cross section. The cool down is performed by spraying a liquefied nitrogen (-196℃) into the cooling unit.



unit : mm

Fig.2 Tensile Test for Prestressing Steel

(3) Test Results

The results of the prestressing steel tensile test are shown in Fig.3 . The lowering specimen temperature from +20℃ to -164℃ increases the tensile strength and 0.2% proof yield stress of the prestressing strand. The rate of increases at -164 ℃ compared to the room temperature are 11% and 13%, respectively.

The elongation of the prestressing strand tends to decrease when the temperature is lowered. The elongation at -164℃ is slightly smaller than the normal temperature. It clears the requirement of 3.5% specified by JIS.

The effect of low temperature on the reduction of cross sectional area is not obvious. The results show fairly good performance as that the reduction at -164℃ does not exceeding 10% to the original area.

The failure surface seems to be ductile in low temperature down to -164 ℃.

Those test results clearly explaine that the properties of the prestressing steel in low temperature comprises with the requirements on the strength and elongation. This means that the structural design can be based on the properties of prestressing steel assuming the use in the normal room temperature.

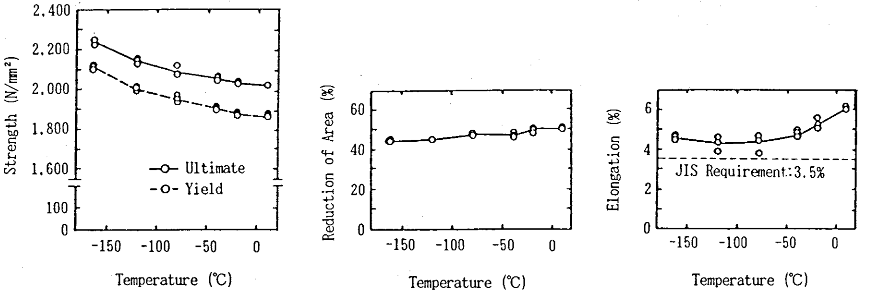


Fig.3 Relationship between Tensile Strength and Temperature for Prestressing Steel (7 wire-strand, Class-B)

3.2 Ductility Test for Prestressing Steel

(1) Specimen

The king wire of 15.2^{mm} 7-wire strand has the total length of 500^{mm} and the gauge of elongation measurement is 300^{mm} long. The notch on the wire has V-shape with 0.05^{mm} bottom radius, and its depths are 0.1, 0.5, 0.7 and 1.0^{mm}.

(2) Testing Method

The specimens are subject to the tension applied at the both ends up to the failure[5]. The testing apparatus is shown in Fig.4. The temperatures of the specimen are varied between the room and -164 ℃.

(3) Test Results

The relationships between the failure stress and the temperature are shown in Fig.5. The data indicate that the temperature limits to avoid a failure at a stress below the yield strength, so called low stress failure, as follows;

For the notch depth of 1.0^{mm}	-40℃
For the notch depth of 0.7^{mm}	-120 ~ -130 ℃
For the notch depth of $0.1 \sim 0.5^{mm}$	-164℃

At -164 ℃, the strength of the wire with 0.8^{mm} notch is affected its strength down to $70^{\%}$ of the nominal tensile strength of the intact steel.

Assuming a possible damage such as 0.1^{mm} deep notch during the manufacturing process or 0.4^{mm} deep notch due to the wedge action at grip ends, these test results show that the prestressing strand certainly keeps its strength and ductility in low temperatures down to -164℃.

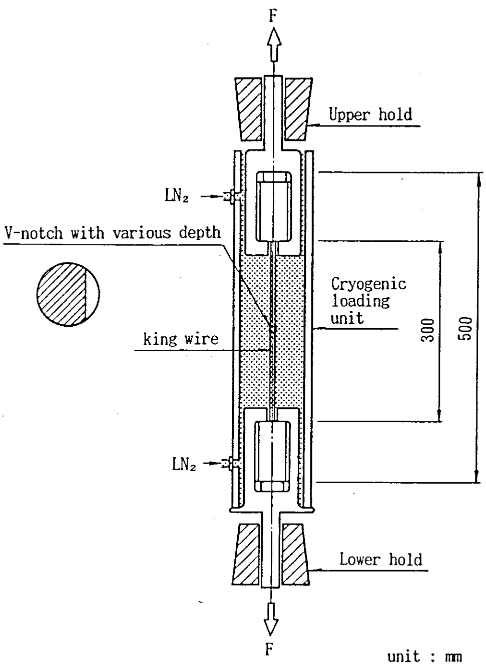


Fig.4 Ductility Test for V-notched Prestressing Steel

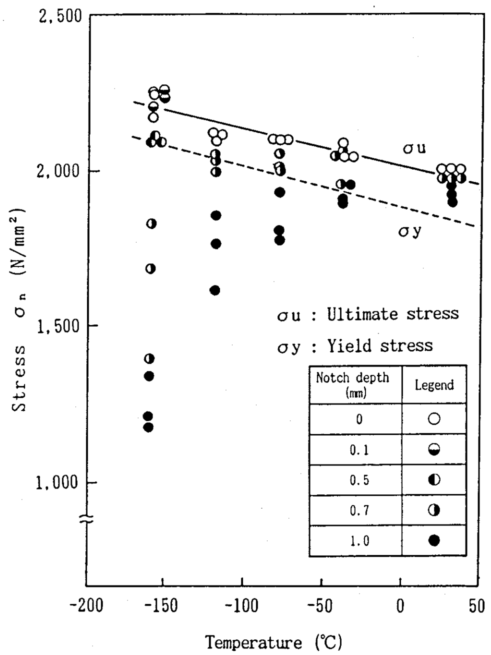


Fig.5 Relationship between Ultimate Stresses and Temperature of King Wire (7 wire-strand, Class-B)

4. DUCTILITY TEST FOR ANCHORAGE AT LOW TEMPERATURES[6]

The Freyssinet V-system, as shown in Fig.6, consists of wedges, an anchorage block and a guide. The ductility of the anchorage block is investigated herein.

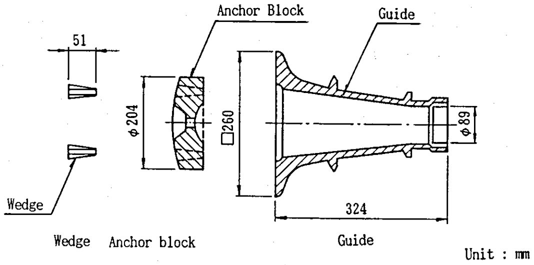


Fig.6 Anchorage Assembly of Freyssinet V-system, 12V15

(1) Specimen

The stress conditions of anchorage block is circumferential tensile force and flexure, while the wedges and guide are primarily the compression member. The anchorage block is made of the alloy steel instead of the ordinary market products of carbon steel. The specimen prepared for the test has the V-notch of 2^{mm} deep.

(2) Testing Methed

In accordance with the impact test specified by JIS, the Charpy impact test rig of 0.3^{KN} weight is used. With reference to WES[7] and ASTM[8] regarding the requirements of the energy absorption, the rate of brittle failure and lateral expansion are specified as follows;

① The average energy absorption should be larger than $48^{N \cdot m}$.
② The average rate of brittle failure should be less than $50^{\%}$.
③ The average lateral expansion should be larger than 0.381^{mm}.

If one of those above requirements is fulfilled at each test temperature, the ductility of the achorage at the given temperature is evaluated as satisfactory.

(3) Test Results

The effect of temperature on the energy absorption and the rate of embrittlement is shown in Fig.7 . At the testing temperature of -80 ℃, the energy absorption is exceeding $60^{N \cdot m}$. The rate of brittle failure is negligible, and the lateral expansion is larger than 0.8^{mm}.

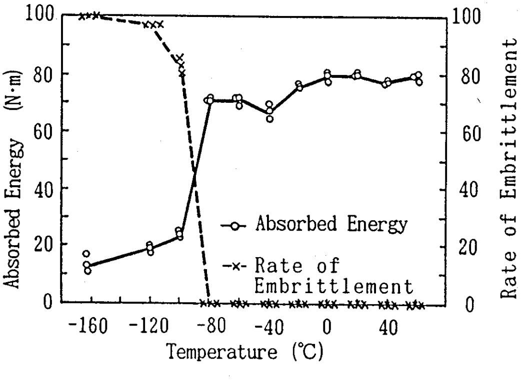


Fig.7 Relationship between Absorbed Energy, Rate of Embrittlement and Temperature of Anchor Block (Freyssinet V-system, 12V15)

5. PROPERTIES OF TENDON ANCHORAGE ASSEMBLY AT LOW TEMPERATURES

The combination of the prestressing tendon of $15.2^{mm} \times 12$-strands (12T15.2) and the Freyssinet V-system anchorage is tested by using a tensile test apparatus and a cold box.

5.1 Tests on Strength, Deformability and Ductility[4]

(1) Specimen

Three specimens are prepared for tests at both ambient temperature and -164 ℃. For tests at the temperatures of -40, -80, -120 ℃, one specimen per each temperature only is used. The one end of tendon, which is connected to the jacking system, is the casting with the white metal in order to avoid the failure at the jacking grip. The other end has the same anchorage assembly as simulating the field practice.

(2) Testing Method

The loading test rig, which has the automatic temperature control system, is shown in Fig.8 and Photo.1. Steps and the temperature control are in accordance with the FIP proposal as shown in Fig.9. This cyclic loading at nearly the yield stress implied that the sensitivity of the assembly to latent defects. The anchorage effects might be increased by the repetitive cyclic loading between the upper bound F_{pyk} (yield strength) and the lower bound F_{po} $(0.9 \times F_{pyk})$. Later the system is tensioned until the failure occur. The overall length of the specimen is 4.5^{m}, and the effective length of the elongation measurement is 2.7^{m}. The recordings of test data are the load-elongation curve, the location of rupture, the reduction of cross section and the stability of anchorage.

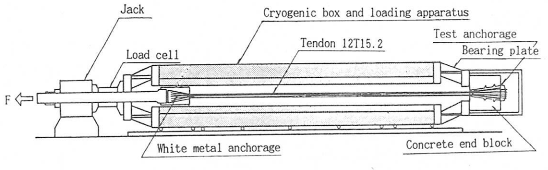


Fig.8 Tensile Test for Prestressing Tendon-Anchorage Assembly

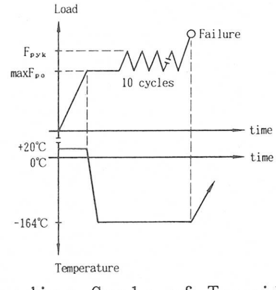


Fig.9 Loading Cycle of Tensile Test for Tendon-Anchorage Assembly

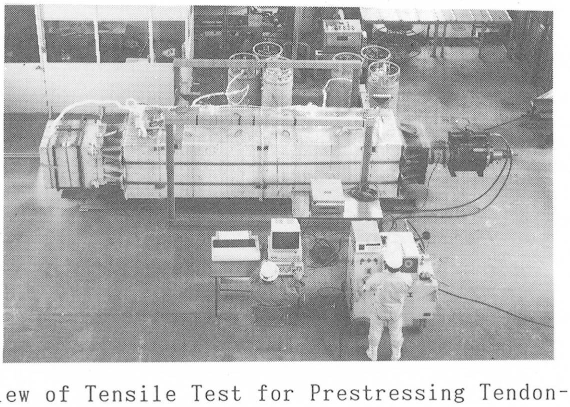


Photo.1 General View of Tensile Test for Prestressing Tendon-Anchorage Assembly

(3) Test Results

Table 3 summarizes the acceptance criteria[9] on the anchorage efficiency proposed by FIP. Figure 10 shows the load-elongation curve, and Fig.11 concludes the performance of the tendon anchorage assembly. The ratio of the tensile strength of the tendon system to the nominal tensile strength of the prestressing steel at ambient temperatures is 1.00 ~ 1.01 (larger than 0.97 requirement), and the elongation at failure of the tendon system is 3.1 ~ 3.9% (larger than 2.3% requirement).

The strength ratio or the anchorage effciency at -164 ℃ is 1.01 ~ 1.02 (comforming to 1.0 requirement), and the elongation is approximately 3% (satisfying the requirement).

Although the specimen temperature decreases, any noticeable decrease in elongation is not observed, and any brittle failure mode does not exist as shown by the ductile failure of rupture surface.

The location of tension failure coincides with the end of the anchorage guide where the tendon is enforced to bend to the diameter of tendon duct.

No defects on the anchorage components are found up to the failure of prestressing tendon.

The test results imply that the prestressing tendon anchorage assembly used here is certainly the ductile structural system in low temperature.

Table 3 Evaluation Criteria of Anchorage Efficiency for Tendon-anchorage Assembly

Temperature	Anchorage Efficiency	Ultimate Strain
Ambient	$\eta_A = \frac{\text{strength of tendon-anchorage assembly } F_{TU}}{\text{nominal strength of prestressing steel min } F_{CU}} \geq 0.97$	$E_U \geq 2.3\%$
Cryogenic (-40℃~-164℃)	$\eta_B = \frac{\text{strength of tendon-anchorage assembly system } F_{TU}}{\text{yield stress of prestressing steel at test temperature } F_{YO}} \geq 1.00$	$E_{UO} \geq E_{PO}+1\%=E_{PU}$ (CEB-FIP) the measured total strain larger than the yield strain of prestressing steel attest temperature

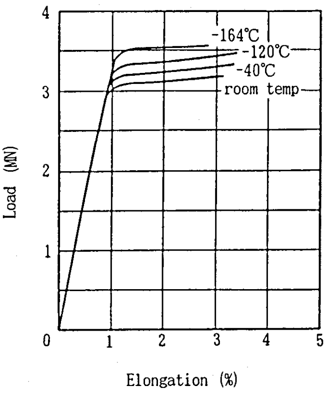


Fig.10 Load-Elongation Relationship (12V15)

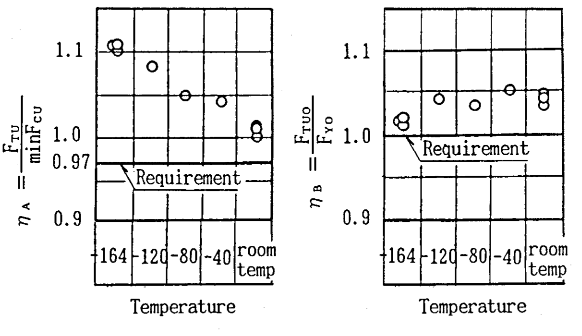


Fig.11 Anchorage Efficiency vs Temperature (12V15)

5.2 Thermal Shock Test for Prestressing Tendon Anchorage Assembly

(1) Specimen

The prestressing tendon anchorage assembly is installed in a reinforced concrete beam, then, the tendon is tensioned by 60% of the nominal tensile strength. The reinforcement and concrete are $300^{N}/_{mm^2}$ of f_{sy} and $40^{N}/_{mm^2}$ of f'_{ck}, respectively.

(2) Testing Method

The thermal shock is imposed by the rapid filling of a liquefied nitrogen into the tendon exposing room and the anchorage, as shown in Fig.12. The time history of strain development is measured along the tendon.

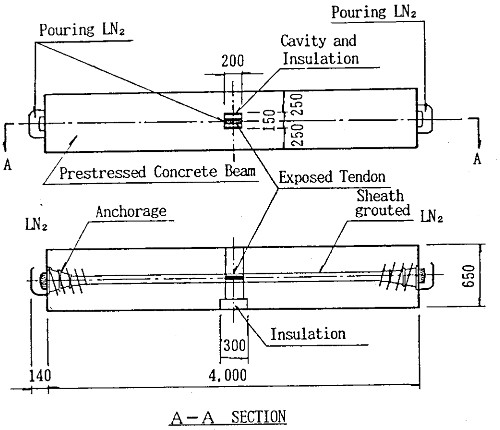


Fig.12 Test Specimen of Thermal Shock Test

(3) Test Results

The thermal shock given at the beam center gradually lowering the temperature of neaby prestressing steel as well as anchorage. The steady state temperature is attained within 5 minutes for the tendon and 10 minutes for the anchorage .

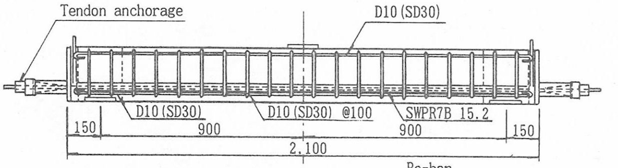
The tensile strains of the prestressing steel and anchorage block are approximately 350μ and 600μ in the longitudinal and circumferential directions, respectively. These strains are for lower than the strains at yielding. No defects in both the prestressing steel and the anchorage are observed. The structural integrity of the prestressing tendon anchorage is reliable even in occurrence of an extreme temperature situation such as the abrupt liquid contact along the tendon or at the anchorage.

6. PROPERTIES OF PRESTRESSED CONCRETE BEAM AT LOW TEMPERATURES

6.1 Flexure Test for Prestressed Concrete Beam

(1) Specimen

The total of 8 specimens are tested, one non-prestressing beam and seven prestressed concrete beams. The prestressed force applied is a half of the yield strength of tendon. The temperatures and the impact speeds are shown in Fig.13. The prestressing tendon is the same as the previous assembly test. The mix of concrete is defined in Table 4. The formwork is removed at the age of 5 days and the moisture curing is continued until 7 days. Then, specimens are cured in air until the testing at 60 days or less.



No.	Specimen Label	Temperature (℃)	Deformation Speed
1	PC-N-0	room temp.	Static
2	PC-60-0	-60	
3	PC-120-0	-120	
4	PC-N-100	room temp.	$100^{cm}/_{sec}$
5	PC-60-100	-60	
6	PC-120-100	-120	
7	RC-120-100	-120	
8	PC-164-100	-164	

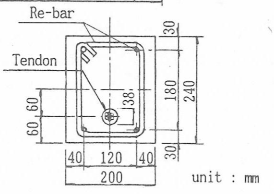


Fig.13 Dimension and Re-bar Arrangement of Prestressed Concrete Beams for Flexure Test with Impact Loading

Table 4 Concrete Mix of Prestressed Concrete Beams

Maximum size of coarse aggregate (mm)	Slump (cm)	Air content (%)	Water cement ratio (%)	Percentage of coarse aggregate (%)	Quantity of material per unit volume				
					Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Additives (kg/m^3)
25	12	4.0	44.0	48.3	163	370	723	1,076	0.862

Note : · Specified strength : 37 N/mm^2
· Cement : Ordinary portland cement
· Aggregate : River gravel, river sand
· Additives : Air entraining and water reducity agent

(2) Testing Procedure

The cooling is done by liquefied nitrogen vapour in the cold box and the temperature control system is automatically to maintain the temperature constant throughout the testing. The beam is loaded by the simple support with a centre point load. In case of the static loading, the load is gradually increased until the tensile failure of the steel. For the impact loading, the induced deformation speed is controled to $100^{cm}/_{sec}$, which is equivalent to the maximum strain rate of tank during earthquake shaking. The overview of the impact loading test is shown in Photo.2.

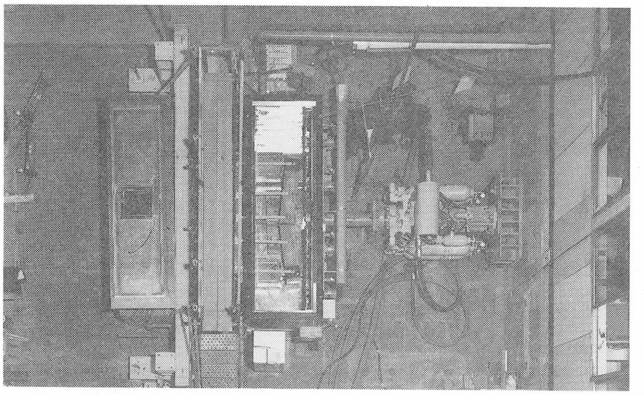


Photo.2 Overview of Flexure Test

(3) Test Results
The failure mechanism is such way that all beams failed in flexure. The failure modes of each specimen are shown in Photo.3. Flexure cracks initiate at the mid-span, then, together with diagonal cracks its propagate to the supports. The compression failure is recognized in the concrete and the tension failure in both reinforcement and the prestressing steel. The difference of number and depth of cracks are not significant in either cases of the static loading and the impact loading. As previously known, the lower in temperature is the larger in crack width and smaller in number of cracks.

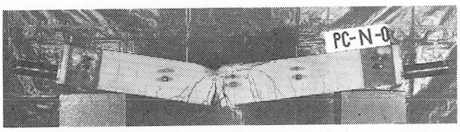
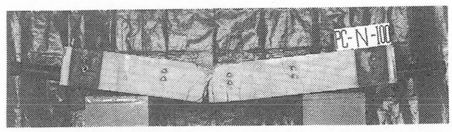
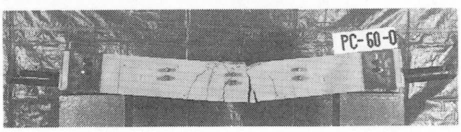
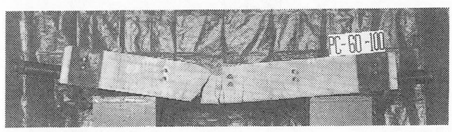
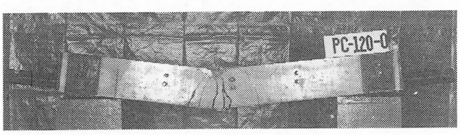
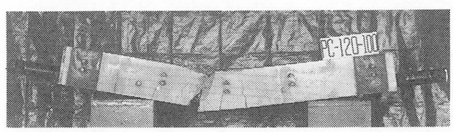
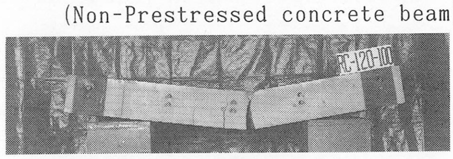
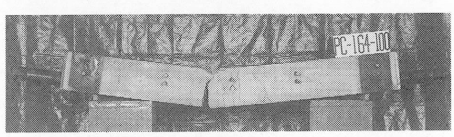
Cases of the Static Loading	Cases of the Impact Loading
No.1 ; PC-N-0 	No.4 ; PC-N-100 
No.2 ; PC-60-0 	No.5 ; PC-60-100 
No.3 ; PC-120-0 	No.6 ; PC-120-100 
	No.7 ; RC-120-100 (Non-Prestressed concrete beam) 
	No.8 ; PC-164-100 

Photo.3 Failure Modes of Prestressed Concrete Beam in Flexure

Figures 14 and 15 show the load-deflection curves of the static loading and impact loading, respectively. The structural behaviours of in both loading tests are identical the all range of elastic, initial cracking and ultimate loading regardless the test temperature.

The effect of low temperature on the ultimate load and maximum deflection are shown in Fig.16 and Fig.17, respectively. It is obvious that the lower in temperature results the larger ultimate load and the smaller in deflection.

The relationship between the absorbed energy ratio and the testing temperature is shown in Fig.18. The energy absorption is obtained by the integration of the load-deflection curve up to the maximum deflection. The absorbed energy ratio of each temperature is the ratio to that of room temperature. The absorbed energy ratio tends to decrease when the temperature goes down. At -164 ℃ the ratio still exhibits 70% of the energy absorption at the room temperature.

The temperature rather than the rate of impact loading speed has more significant effect on the ultimate load, deflection and absorbed energy. The prestressed concrete beams tested herein have shown sufficient ductility in terms of energy absorption failure even at -164 ℃.

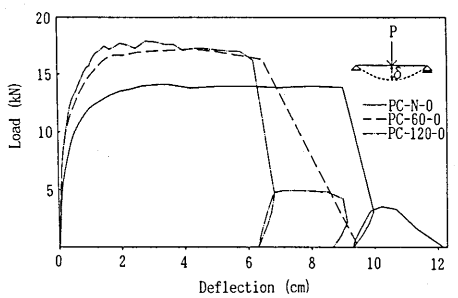


Fig.14 Load-Deflection Curve of Concrete Beams under Static Loading

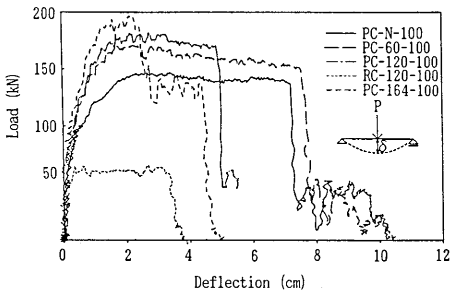


Fig.15 Load-Deflection Curve of Concrete Beams under Impact Loading

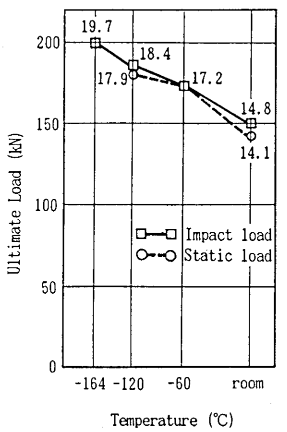


Fig.16 Relationship between Ultimate Load and Temperature of PC-Beams

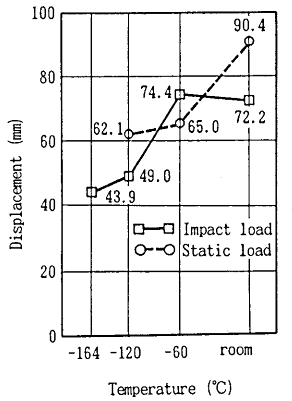


Fig.17 Relationship between Maximum Deflection and Temperature of Concrete Beams

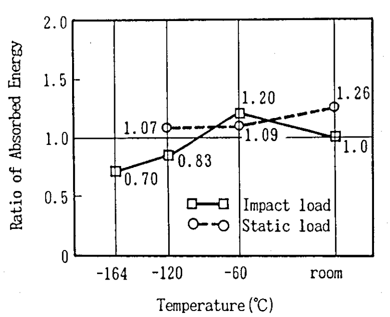


Fig.18 Relationship between Absorbed Energy Ratio and Temperature of Concrete Beams

6.2 Liquid-tightness of Prestressed Concrete Beam under Liquid Attack

(1) Specimen

The test beams are designed to have the re-bar ratio and the prestress as shown in Table 5. The dimension of the beams and re-bar arrangements are shown in Fig.19. Both ends of a beam are treated with an insulation blanket to isolate the beam from the heat transfer supplied from atmosphere. The material specifications of these test beams are the same as the impact loading test.

(2) Testing Method

The thermal shock is applied by directly pouring the liquefied nitrogen(-196℃) on the top surface of the beam. The restraint forces are imposed at the both ends of the beam in order to investigate the bending moment of the beam due to the time-dependent thermal gradient. Once the temperature distribution reaches to the steady-state, the tensile axial force is applied at the beam ends to develop the crack widths further. The maximum strain developed along the reinforcing bars at very moment of spillage initiation is carefully investigated. The spillage is observed by the thermocouples attached at the bottom surface of the beam as well as visual inspection.

Table 5 Design Parameters of Prestressed Concrete Beams for Thermal Shock and Liquid-tightness Tests

No.	Specimen Label	Tension Steel Ratio (%)	Prestress (N/mm²)	Steel Arrangement
1	S 5-P10	0.55	1.0	Re-bar 2-D22 Tendon 1T15.2 Re-bar 2-D22
2	S10-P10	1.10	1.0	Re-bar 4-D22 Tendon 1T15.2 Re-bar 2-D22
3	S 5-P30	0.55	3.0	Re-bar 2-D22 Tendon 3T15.2 Re-bar 2-D22
4	S10-P30	1.10	3.0	Re-bar 4-D22 Tendon 3T15.2 Re-bar 2-D22

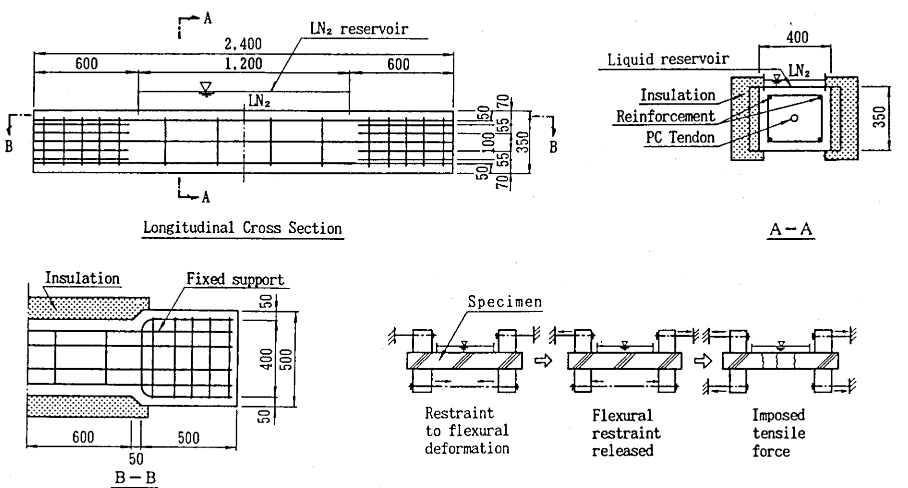


Fig.19 Test Specimen and Loading Method of Concrete Beams for Liquid-tightness Test

(3) Test Results

The thermal shock rapidly cools the upper part of the specimen due to the direct contact of LN_2. Then, the temperatures in the specimen approach to the linear distribution from the top to the bottom due to the heat transfer within the concrete, as shown in Fig. 20. Even transverse tension cracks are developed along the upper surface of the beam by the restraint moments, neither the liquid spillage nor the abnormal structural behaviour occur.

The restoring moments and the associated re-bar strains are shown in Fig. 21 and Fig. 22, respectively. The nonlinear finite element analysis using material properties at low temperatures fairly well simulates the behaviour of the test beams. The reason of slightly larger the restoring moments obtained by the test compared to the analysis seems to be attributable to that the analysis do not include the concrete strength remained in a non-cracking zone between two cracks The tension stiffening effect should be taking into account for the accurate estimation of flexural rigidity of the crack developed concrete structure. The ratio of the maximum restoring moment to that of the derived from the elastic analysis, equivalent to the residual flexural rigidity, is somewhat between 0.40 and 0.65. The ratio tends to increase when the reinforcing bars and the prestressing force are increased.

Figure 23 shows the relationship between the strain of the lower reinforcement and the temperature at the beam bottom, which data are obtained the particular moment of that cracks are heavily developed by the tensile force applied at the beam ends. Test beam of No.1(;S5-P10) shows a rapid temperature drop to at the beam bottom. The spillage is noticed when the re-bar strain reachs approximately 2500μ to 2600μ. The similar behaviour is also observed No.3 (;S5-P30) specimen, which the maximum strain is 1900μ. The beams of S-10 series are designed to have double of the reinforcement compared to the S-5 series. The former series of beams does not occur any significant temperature drop up to the steel strain of 2200 ~ 2500 μ. Before initiating the liquid leakage, the yielding and failure of the S-5 beams occur due to the external loadings.

It is worthwhile to note that the prestressed concrete beam or structure seems to be liquid-tight if the maximum tensile reinforcement strain of the sufficiently reinforced structure is not exceeding 2000 μ.

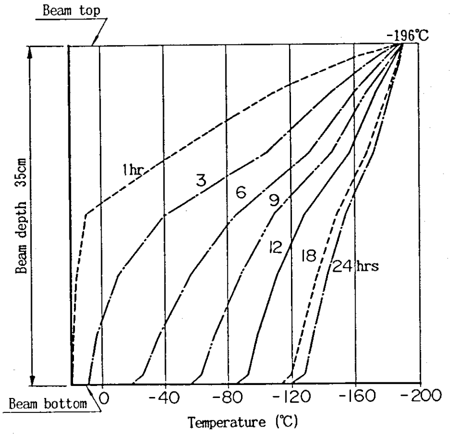


Fig.20 Time-Temperature Distribution History of Concrete Beam at Liquid-tightness Test

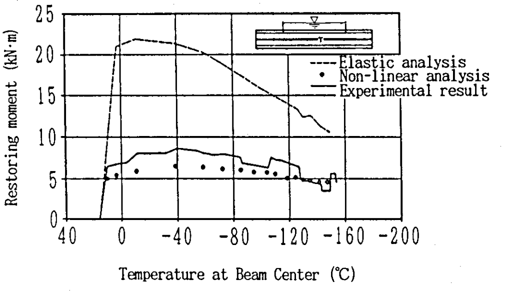


Fig.21 Change of Beam Restoring Moment depending on Concrete Temperature at Beam Center

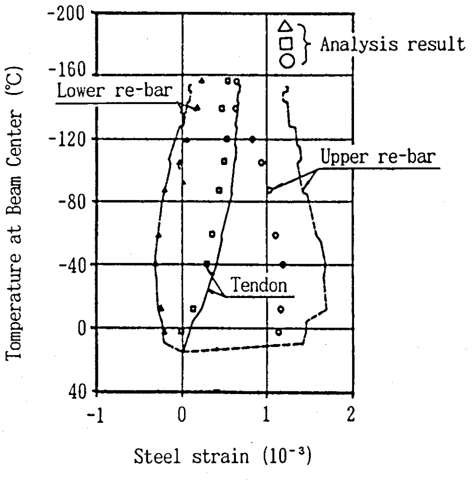


Fig.22 Strain Change of Prestressing Steel due to Temperature Change (Specimen No.1 ; S5-P10)

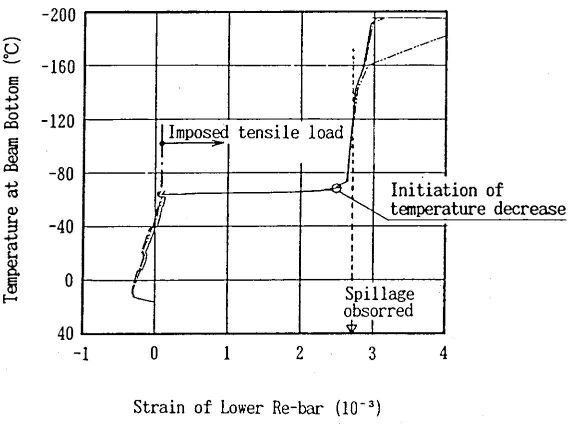


Fig.23 Relationship between Strain of Lower Re-bar and Temperature at Beam Bottom (Specimen No.1)

7. CONCLUSION

7.1 Load Bearing Capacity of Prestressed Concrete

(1) It is found that the strength and elongation of the prestressing steel at temperatures from room to -164℃ satisfy and exceed the JIS requirements. The prestressing steel is a reliable material for the use in low temperatures in terms of ductility. The V-notch tension tests at the temperature of from room to -164 ℃ clearly show that no significant decrease in the strength and ductility exist.

(2) The Charpy V-notch test for the Freyssinet V-system manufactred by the cryogenic specifications shows that the transition temperature of ductile to brittle behaviour is below -80℃.

(3) The anchorage efficiency test in accordance with the FIP proposals indicates that the prestressing tendon anchorage assembly fulfills the requirements in low temperature down to -164℃.

(4) The flexure test for the prestressed concrete beam yields the strucural behavior that lower temperature increases the ultimate load and decreases the deflection. The bending or shear failure of the beam occurs only after the ultimate load is reached. The deformability of the beam necessary as a ductile structure is also confirmed to be sufficient. The impact load resistance (absorbed energy) of the beam at -164 ℃ is 70% of that at room temperature. The embrittlement is unlikely to occur in the course of failure process as well as the state of rupture. The prestressed concrete structure can be considered to ductile down to-164 ℃.

(5) The resistance of the prestressing tendon anchorage assembly to the abrupt thermal shock is investigated by pouring a liquefied nitrogen to the tensioned and grouted prestressing steel and the anchorage. The system tested herein demonstrates the structural integrity throughout the rapid temperature drop.

(6) When a prestressed concrete beam is subject to a thermal shock and a severe temperature distribution due to the direct contact of LN_2, neither liquid spillage nor unexpected abnormal structural behaviour is occurred except the development of tensile crackings. It is found that the nonlinear finite element analysis as equal as the transient state temperature analysis are useful tools to evaluate the structural behaviour of the prestressed concrete subject to thermal stresses.

7.2 Liquid-tightness of Prestressed Concrete Beams

In case of prestressed concrete beams are subject to a considerable temperature gradient, the liquid spillage does not occur as long as the steel strain remains within 2000μ. This conclusion provides a fundamental design criteria on the design practice of a liquid-tight structure.

8. FUTURE DEVELOPMENT

The findings or the prestressed concrete in low temperature obtained from this study are applicable to various types of structures for low temperature use, such as the offshore platforms in the cold regions.

The results of this study have been sucessfully incorporated in the construction of three prestressed concrete dikes[13] for the 80,000kℓ LNG tanks which is the first application of prestressed concrete in LNG facilities in Japan. In future there will be more refinement on those study topics, and the further reserch efforts will be added to provide the necessary technical informations for the safe and economical construction of the refrigerated gas containment system.

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