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Assessment of Mechanical Properties of Structural Materials for Cryogenic Application

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Report by

F.S. Rostásy

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Preface
to the Report „Assessment of Mechanical Properties
of Structural Materials for Cryogenic Application
(Status 1988)

This report was written by Prof. F. S. Rostásy, Institute of Building Materials, Structural Concrete and Fire Protection (IBMB) of the Technical University Braunschweig, Germany. It was finalized in June 1988. The objectives of report are outlined in the Foreword to that report written by Prof. Bruggeling who at that time was the chairman of the FIP Commission “Prestressing Steels and Systems”.

From the beginning of work on the report it was the goal to have it published as a FIP document after finalization. The FIP Editorial Board however declined Prof. Bruggeling’s request of publication. On the contrary, the FIP Editorial Board decided to transfer the report to the Library of the Institution of Structural Engineers without publication but for internal use only. There, on the shelve of library, the report stayed more or less unknown to science and practice for 20 years.

From 1990 on and over the period of 10 to 15 years, research and development of prestressed concrete tanks for the storage of liquefied natural gases were performed on a rather low-key pace. At present, however, the interest on this topic is markedly increasing. This fact can be explained with the world-wide need for the assurance of different primary energy sources in the future.

In view of this development, IBMB decided to print the report in its own scientific series. Such procedure will redeem the 1988 report from obscurity and will transform it into a quotable literature source.

F. S. Rostásy

July 2011

FOREWORD

It is with a great pleasure that I introduce this report of the F.I.P. Commission on prestressing steel and systems dealing with the "ASSESSMENT OF MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS FOR CRYOGENIC APPLICATIONS".

The importance of this report is that it offers a base for the comparison of test results regarding mechanical properties of materials under cryogenic conditions of investigations, carried out in different laboratories. In this way the design of **this** type of structures can be based on data, which are widely accepted. The tests, described in the report, are not limited to materials used in storage vessels for liquefied gases. They can also be applied for materials, used in concrete structures in areas with low or very low temperatures, such as in the arctic. The test methods can therefore be applied by laboratories, which are involved in the investigation of materials.

This report has been written by Prof. Dr.-Ing. F.S. Rostásy from the Technical University of Braunschweig of the B.R.D., member of the F.I.P. commission on Prestressing steels and systems. Several members of this commission have reviewed his proposals critically. The commission is very grateful to Prof. Rostásy for the work he did to write, to edit and to prepare the final version of this report, ready for publication. He really fulfilled a great task almost on his own. Therefore, this report bears his name as the author.

It is a strong wish of the F.I.P. commission that this report will be used as a largely accepted basis for the assessment of the mechanical properties of the materials to be used in (prestressed) concrete structures, subjected to low, very low and cryogenic temperatures.

Prof.dr.ir.A.S.G.Bruggeling
Chairman F.I.P. Commission
"Prestressing steel and systems"

**Assessment of mechanical properties of structural materials
for cryogenic applications**

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7. LITERATURE

1. INTRODUCTION

The design of elements of a storage tank for refrigerated liquefied natural or technical gases is based upon the basic requirements for structural safety, integrity and tightness. Furthermore, a series of conditions and loads for the various stages of a tank during service life and in case of abnormal events must be formulated for each tank design. The structural engineer in charge has to assess resistance and response of the systems and elements from static and dynamic analyses. For this task he needs reliable information on the mechanical behaviour of structural materials and prestressing systems subjected to extremely low temperature, especially in the form of characteristic and admissible values /1/. Neither requirements nor conditions and loads nor design values for materials and systems could be agreed upon internationally, albeit standardized. However, there exist certain national standards in some countries or equivalent specifications of gas associations and other bodies.

It is the scope of this report to contribute to an internationally agreed assessment of the properties of materials and prestressing systems under cryogenic conditions. This assessment is performed exemplarily for a LNG-double containment system in prestressed concrete. By so doing a guideline for other types of RLG and tank design with respect to testing of materials and to formulation of material requirements is presented (RLG, refrigerated liquefied gas).

2. CONDITIONS AND LOADS

2.1 Regimes of design and construction

Several regimes need to be considered in the design and construction of a cryogenic storage unit (/2/, /3/ and /5/). Each regime is characterized by its own loading combinations and design considerations. In /5/, the following regimes are distinguished:

- construction
- testing and commissioning
- operating
- maintenance
- abnormal regimes

For these five regimes, the load combinations and design aspects relevant to operating and abnormal conditions are briefly dealt with here. To provide the necessary definitions and nomenclature, Fig. 1 shows a schematic section through a double-containment vessel; for other types of design see /5/. The position of the liner has been assumed to be at the inner surface of the outer wall, there are, however, other possibilities.

2.2 Operational conditions and loads

During normal service the prestressed concrete and reinforced concrete members will be subjected to a series of loads and effects, which either act statically or change only slowly with time. These loads are:

(a) Dead load:

dead weight of the concrete members and others; weight of installations (piping, valves, platforms, railings, etc.); weight and pressure of insulating materials on adjacent members

(b) Prestressing forces:

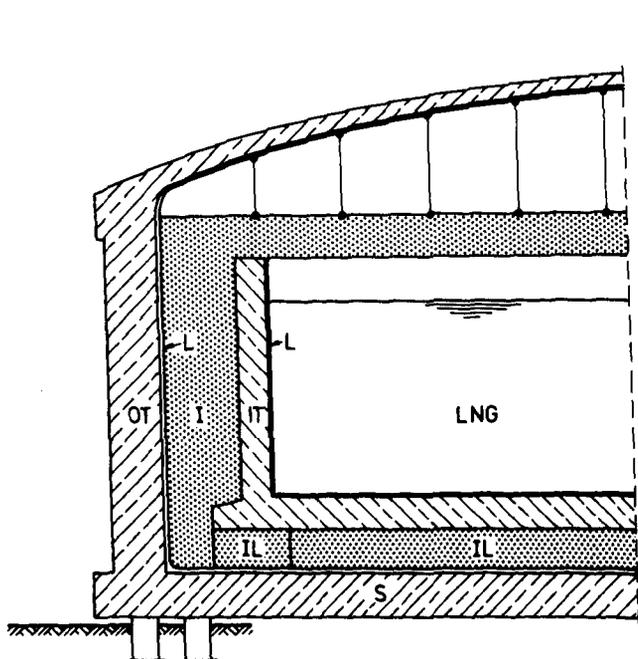
general magnitude and local variations of circumferential and vertical prestressing forces in walls and of circumferential and orthogonal prestressing forces in bottom slab

(c) Live loads:

loads on roof, platforms and access-ways, pressure of water (only during water-tightness test), pressure of gas (during gas-tightness test and in operation), weight and pressure of liquefied gas; permissible overpressure or underpressure during regular service, ground water pressure, soil pressure, and other sources of live load

(d) Environmental loads and effects:

wind, snow, variations of ambient temperature, moisture transfer.



- D reinforced concrete dome
- OT prestressed concrete wall of outer tank
- S prestressed concrete slab
- IT prestressed concrete inner tank
- I non-loadbearing insulation
- L liner
- IL loadbearing insulation

Fig. 1: Main components of a double containment LNG storage vessel with a steel inner tank (example)

- (e) Settlement:
uniform and/or differential settlement
- (f) Temperature conditions:
temperature changes in concrete members during regular service and also in course of cool-down and warm-up operations.

2.3 Abnormal conditions and loads

The storage of liquefied gases always involves a potential danger. Thus, the design of storage vessels must allow for a series of abnormal or extraordinary conditions and relevant loads. These conditions have, up to now, not been standardized; they have been dealt with independently for each vessel project by the owner and the engineers responsible. Hence, the conditions cited below should be regarded as examples from past experience.

Abnormal conditions may arise from external or internal events. The following are of internal origin:

- (a) Overfilling of the inner tank beyond the specified limit,
- (b) Transgression of the specified limits of overpressure and underpressure of the gas above the liquid level,
- (c) Low temperature shock
In conjunction with overfilling, leakage of the inner tank or total failure of the inner tank, the surrounding members will be subjected to thermal shock. In the hypothetical case of sudden failure of the inner tank, impulse loads will be generated.
- (d) Gas explosion within the annular gap (or within the space between safety wall or bunds and tank due to escape of gas from tank),
- (e) Roll-over,
- (f) Burning of tank contents.

The following conditions of external origin usually have to be considered:

- (g) Earthquake,
- (h) Pressure wave due to explosion in the vicinity of the tank (nearby explosion),
- (i) Impact,
- (j) Nearby fire,
- (k) Natural phenomena, such as floods and hurricanes.

3. RELEVANT TEMPERATURES AND STRESS CONDITIONS

3.1 Introductory remarks

It is the aim of the following section to develop the relevant temperature and stress conditions during operational and abnormal events. Knowledge of these conditions is the prerequisite for realistic testing of materials and for rational formulation of requirements. Only such conditions will be considered which create cryogenic temperatures in the structural members.

The relevant temperatures of the structural members and materials depend on the liquefaction temperature of the stored gas and on the type of design. Thus, it is not possible to present a set of generally applicable temperature values valid for all types of design. The relevant values will be developed for a double-containment LNG-tank design with a prestressed concrete inner tank as shown in Fig. 1. For any other type of design and/or for a liquefied gas other than LNG the exemplary method presented here may be adopted in a similar way (LNG, liquefied natural gas).

3.2 Temperature and loading condition during service

3.2.1 Prestressed concrete inner tank

Once the inner tank of a double-containment system has been cooled to the operating temperature of about $-165\text{ }^{\circ}\text{C}$ for LNG in a controlled fashion, a steady state of temperature is attained, primarily in those regions of the inner tank which are in contact with the liquid. Above the level of liquid, which varies in course of operation, the temperature of the gas atmosphere may be considerably

above liquefaction temperature. Temperature variation across the thickness of the wall and in the vertical direction will cause restraint effects. Temperature variation with respect to time will vary only between fairly narrow limits.

Temperature changes of a great range of about 180 to 190 °C will only arise in the case of total depletion of the inner tank and the complete rewarming of the structure to ambient temperature (e.g. in the maintenance stage). Wherever possible, this is avoided. Again, rewarming and consecutive cooling will be carried out in a controlled fashion to diminish detrimental thermal restraint action. Stresses in the service state will vary within certain ranges and slowly: static stress conditions.

The magnitude and distribution of temperatures in the cylindrical wall and in the bottom slab in the steady state of service also depend on thickness, arrangement, and insulating capacity of insulating materials and on the dimensions of the structural concrete members. Thus, no exact values of temperature can be presented. They have to be calculated for each design with the principles of heat transfer. Variation of temperature across a member's thickness will be kept small in order to restrict heat loss and boil-off-rate.

3.2.2 Prestressed concrete outer wall

The temperature of the external surface depends mainly on the climatic conditions. For instance, in Central Europe it will vary between - 20 °C in winter and roughly + 50 °C in summer.

The temperature of the inner surface of concrete and of the liner depends on the properties of the thermal insulation within the annular gap. The temperature at the inner face should be as high as possible to keep heat losses and, thus, the boil-off-rate, as low as possible. Furthermore, the temperature difference across the wall's thickness should be small to restrict thermal restraint actions during service. A crossfall of 20 °C or so is the normal value.

3.2.3 Prestressed concrete slab

The temperature of the inner surface depends on the thickness of the load bearing insulating layers below the inner tank. For the identical reasons as mentioned before, the inner surface temperature should not be too low. Usually, the slab will be heated to avoid freezing of the subsoil and to keep the temperature gradient small. In this case the concrete temperature will vary between 0 and + 5 °C.

3.2.4 Reinforced concrete dome

The suspended thermal insulation above the inner tank is dimensioned in such a way that the ingress of heat and consequently the boil-off-rate can be restricted to the desired value. The temperature of the gas atmosphere above the insulation will vary considerably: 0 to - 50 °C.

3.3 Thermal shock due to local cold spot on the inner surface of the outer wall and slab

3.3.1 Causes of cold spot

One of the abnormal events is the temperature shock loading within a limited contact area along the inner surface of the outer tank. The structural members which may come into contact with the LNG are the p/c-slab and the p/c-outer wall.

The possible causes of a local thermal shock, often called "cold spot", are: a leak in the inner tank or accidental overfilling. Overfilling may usually be disregarded because of systems of level control. A leak in the inner tank must be taken into account although it is of low probability. It may be caused by a defective weld in the case of a steel tank or by wide cracks in the case of a p/c-inner tank in conjunction with weld cracks in the inner liner. Reliable measures for the detection of cold spots are part of the permanent performance control of the tank system.

A cold spot may appear on the inner surface of the slab and on the bottom region of the wall. The likelihood of a cold spot in higher regions of the wall decreases with the distance from the bottom. The location of an internal thermal shock is unpredictable, just as its possible size is unforeseeable.

In some regulations, rupture or leakage of external LNG-carrying pipes has to be considered. The location of the thermal shock area on the top of the dome due to this source is restricted and affects the external surface of the r/c-dome and of the p/c-outer wall.

3.3.2 Possible size of cold spot

The following model for a cold spot with respect to spreading and time-function is often employed. The flaw through which leakage of LNG may occur is assumed to be of small size, although quantification of the size is difficult. Consequently the flow of LNG and the area of contact, which probably increases with time, will be limited. A limited cold spot does not impair the overall or even local load-bearing capacity of a p/c-member. Its effects include transient stresses due to thermal restraint. The importance of a cold spot has to be sought in its influence on the gas-tightness and fluid-tightness of the structural member. The cold spot may also lead to increased gas pressure within the tank.

The geometrical model of a local cold spot is shown in Fig. 2. As the effects of thermal stresses increase with the magnitude of total restraint, the cold spot can be modelled by a circular contact area within an infinitely large plate. Within the contact area, which may steadily increase, the LNG-temperature acts as a time-step-function. Fig. 2 also shows two possible solutions for liner design. In one case the cold spot will be directly on the liner, which is usually a low-temperature resistant steel; in the other case the LNG acts on a layer of resin foam, which serves as an insulant against thermal shock. In previous designs, a certain fictitious size of the cold spot was chosen, for instance a circular shock area of 12 to 15 m².

3.3.3 Review of test results

Extensive research has been carried out to study the behaviour of unreinforced, reinforced and prestressed concrete slabs subjected to a circular cold spot by LN₂. The most extensive investigation was performed by Iványi and Schäper /6, 7, 12/. In a first series of tests on plain concrete slabs without a steel liner on the cold side, the process of thermal cracking was investigated. Fig. 3 shows that in the first phase of cracking a circular crack is formed around the shock-area. Its diameter exceeds somewhat that of the shock area.

The crack extends over the total thickness of the slab, with the crack width ranging between 0.2 and 2 mm. The crack's surface is perpendicular to the slab's surface. In the second phase of cracking, radial cracks develop; in the third phase an additional crack branching occurs. In a second test series the beha-

viour of reinforced slabs was studied. The slabs were reinforced on both faces with an orthogonal mesh of deformed bars; the reinforcement ratio was varied within a wide range. It was found that the first circular crack was formed in the same fashion as for the plain slabs.

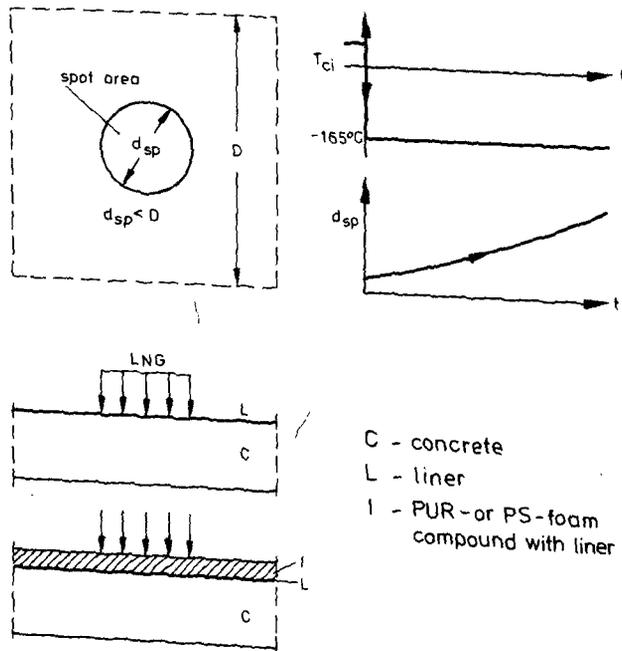


Fig. 2: Model of thermal shock area

Due to the extensional stiffness of the orthogonal net of reinforcing bars on both faces of the slab, however, additional circumferential cracks developed. This is shown schematically by Fig. 4. Because the stiffness of bond increases considerably at low temperature, the reinforcing bars behave as stiff springs bridging the cracks. Thus, the restraint is not totally relieved by the first circular crack. The authors found that the process of consecutive cracking is not markedly influenced by the diameter of the cold spot as long as the restraint is high enough ($D/d_{sp} \geq 2.7$). The width of cracks decreases with the ratio of reinforcement, though not linearly. The cracks closed up entirely upon rewarming of the slabs to ambient temperature, even when using very low ratios of reinforcement.

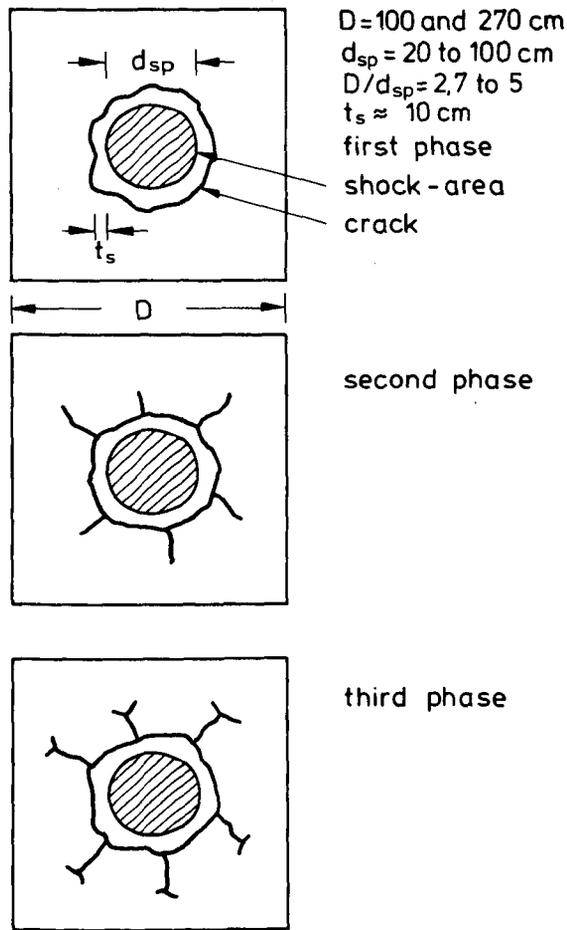


Fig. 3: Cracks due to cold spot in plain concrete slabs (tests by /6/)

Tests on reinforced concrete slabs of greater thickness and with larger dimensions were performed by Biervliet and Mortelmans /8/ and by Rostásy and Wiedemann /9/. In /8/ a slab of 5 m diameter, 40 cm thickness and a shock-area of 2 m diameter was tested. Again, several circumferential cracks were formed with a diameter of $d_{cr} \approx d_{sp} + t_s$. The cracks originated between 1 and 14 hours after shock. The first cracks on the cold top surface appeared after one hour; the first cracks on the bottom side occurred after seven hours. The temperature in the top plane of reinforcement was at the time of first cracking between -100 and -120 °C. The maximum steel strain in the cracked section was about $+1,7$ ‰.

In /9/ a slab of 4 m side length, 40 cm thickness and a shock-area of 40 cm diameter was tested. The results correspond essentially to those of /8/. The lowest steel temperature was -130 °C.

Fig. 5 shows the crack patterns of these tests. The width of the cracks on the top side of the slab of /8/ varied in the cold state between 0.1 and 0.5 mm; the cracks closed entirely upon rewarming. The crack widths of /9/ were considerably narrower because of the much higher reinforcement ratio.

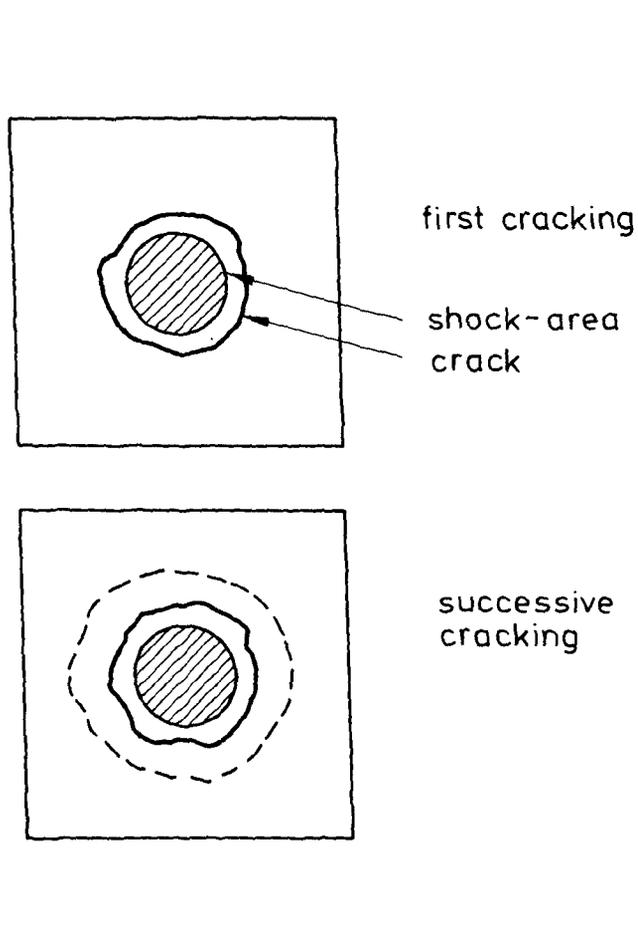


Fig. 4: Cracks due to cold spot in reinforced slabs (tests by /7/)

3.3.4 Relevant temperatures of steel, tendon, and concrete in the case of a cold spot

3.3.4.1 Reinforcement

All these tests proved that the reinforcement does not suffer a sudden shock from the cryogenic temperatures. Also the steel stresses due to thermal restraint are built-up gradually. The reason for the delayed build-up of low temperature and of stresses in the reinforcing steel is due to the thermal inertia of concrete. Depending on the thickness of the concrete cover above the bars on

the cold side and on other factors, the steel temperature within the uncracked concrete regions remains above the boiling temperature of the LNG or, generally, of the liquefied gas. For the sake of safety (ingress of LNG into a crack) the relevant minimum temperature, at which the mechanical properties of the steel positioned at inner surfaces of the outer tank are to be tested, should correspond to the LNG-temperature. The influence of stress-rate is negligible.

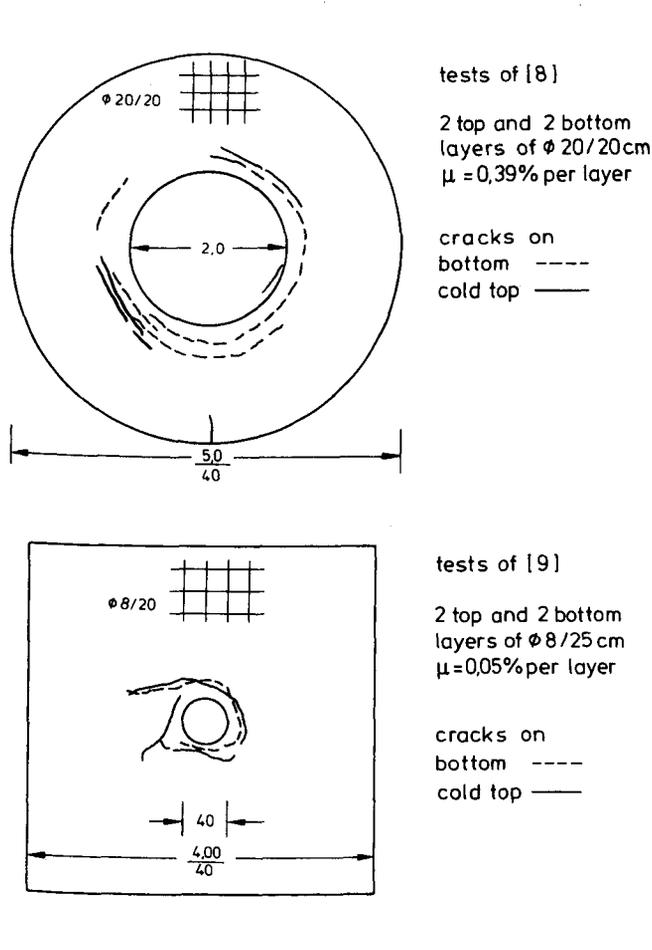


Fig. 5: Crack patterns of the shock tests by /8/ and /9/

The temperature in the bottom layer (warm side) of reinforcing bars is higher than in the top layer (cold side). In /9/ - 40 °C were reported. The temperature at the bottom surface seems to increase with the diameter of the shock area. Bruggeling /2/ determined by calculus an external surface temperature of - 30 °C for an ambient temperature of + 20 °C. Thus, considering a winter temperature of - 20 °C the relevant minimum temperature, at which the mechanical properties of the external steel should be known, would be about - 50 to - 60 °C. Again, the strain-rate is normal.

For the reinforcing steel on the external, warm surface of the outer tank, usually normal deformed bars with a yield strength between 400 and 500 N/mm² at room temperature are chosen without establishing their behaviour at a temperature of - 50 to - 60 °C. While some types of deformed bars have transition temperatures below this relevant minimum temperature, others do not.

In none of the tests was a steel liner mounted on the cold side of the slabs. It is not likely that the presence of a steel liner influences the temperature distribution in the slab if the cold spot acts directly on the liner. However, if the steel liner is protected by resin foam, as in Fig. 2, the cold surface temperature of the liner, the concrete, and the reinforcement will be sharply increased. Whether this benevolent effect can be taken into account when stipulating the minimum relevant temperatures for materials testing depends on the reliability of the insulating foam during thermal shock, on the foam's durability, and on the boldness of the tank's owner.

3.3.4.2 Prestressing tendons

The temperature in the prestressing tendons of the outer tank in the case of a cold spot depends upon several factors. The most decisive is the position of the tendon within the section of the wall and of the slab with respect to the concrete cover within the contact area of the thermal shock. Because the arrangement of the tendons and anchorage assemblies within the section of the members may differ in the various designs, no definite values of temperature can be presented here. Only in the case of post-tensioning of the outer tank by the wire-winding technique is the location of the prestressing steel definitely known beforehand.

It is often argued that the relevant temperature in the tendons and anchorages of the outer tank will be definitely higher than the LNG-temperature in the case of a cold spot. This argument is supported by the steep temperature gradient during the transient heat flow. However, this argument neglects the possibility of cracks in the concrete, and the liner as well, through which ingress of LNG may occur. Since this possibility cannot be entirely precluded, the relevant temperature, at which the mechanical properties of the prestressing steel and of anchorage assemblies are to be tested, should correspond to LNG-temperature. Certainly, the relevant temperature for the testing of tendons and anchorages for a post-tensioned inner tank must be the LNG-temperature.

3.3.4.3 Concrete

If the cold spot acts directly on the concrete or on a liner, the concrete is subjected to a thermal shock within the first few centimetres of the cover. The tests of /12/ have shown that the surface of concrete approximately adapts to the boiling temperature of the RLG. The build-up of low temperature with increasing depth from the surface is rather slow. Very steep temperature gradients and high thermal eigenstresses arise. These effects lead to narrow cracks perpendicular to surface. These cracks are in fact benevolent with respect to the behaviour of the member under the ensuring restraint actions because they reduce the bending and extensional stiffness of the member and, consequently, the combination of actions leading to the first primary restraint cracks.

In none of the tests, spalling of concrete in the surface region occurred. High strength concrete with an effective water-cement-ratio ≤ 0.45 does not suffer frost damage even if the physically bound excess water could not exsiccate because of a steel liner.

Thus, the relevant minimum temperature, at which the mechanical properties of concrete are to be tested, should correspond to the LNG-temperature. The rate of change of temperature within the first few seconds and millimetres of concrete is certainly very high. It can be simulated by immersion of the concrete specimens in liquid nitrogen. However, this type of testing may only suffice to explore possible losses of strength due to sudden shock. Thermal deformation and the stress-strain diagram at low temperature cannot be measured if immersion is adopted. To establish the mechanical properties of representative specimens for the first 10 cm of cover adjacent to the cold contact area, a controlled cooling and heating rate of 2 K/min should be chosen.

3.4 Large scale thermal shock

3.4.1 Total and slow filling of annular gap

The local thermal shock, which has been dealt with in the previous chapter, causes restraint forces only within the region of the cold spot and its vicinity. Reasons of safety also require consideration of an abnormal condition during which the annular gap between inner tank and outer wall becomes totally filled with LNG. Besides a large scale thermal shock of the entire inner surface of the outer tank, normal forces, shear forces and bending moments due to liquid pressure and thermal gradients will be generated. The whole storage system will also be subjected to rapidly rising gas pressure. All statements regarding relevant testing temperatures of sec. 3.3 are also valid for this case.

If the outflow is generated by overflowing or by leakage of the inner tank it will cause a steady build-up of LNG-pressure head. Thus, static conditions prevail with respect to the load history.

3.4.2 Liquid impact on the outer tank

This abnormal load case is only conceivable if the inner tank is made of steel. It is the consequence of the sudden ripping-open process of the steel tank along a vertical generatrix of the cylinder wall due to rapid crack formation. A prestressed concrete inner tank cannot fail in this mode, because of its multitude of individual tension members (prestressing wires and reinforcing bars). As the wall bursts, two liquid waves run in opposite directions and collide just opposite the crack. Thereby, a liquid impact acting normally to the inner surface of the outer wall and within a certain sectoral angle will be caused. The opposite wall of the inner tank may also be thrust against the outer wall. Depending on the damping effect of the thermal insulation within the annular gap, the velocity of the ripping-open of the inner tank, the tensile and bending stiffness of the concrete members and on several other factors, a dynamic surge of pressure will arise. Bomhard /10, 13/ investigated analytically the behaviour of a prestressed outer tank under liquid impulse. The impulse time was varied. The dynamic pressure was found to be up to six times the static pressure for certain assumptions. Fig. 6 shows schematically the time-function of the dynamic pressure. It may be concluded, that the liquid impulse will certainly be combined with high stress rates in the materials.

For the load case of static LNG-pressure on the prestressed concrete outer wall and slab, the relevant temperatures and their rates of change which should be employed for the testing of materials, can be assumed as for local thermal shock. The rate of stress in the materials corresponds to static conditions.

In the hypothetical load case of liquid impulse following the sudden bursting of the inner tank, the structural materials of the prestressed concrete will be subjected to high stress and/or high strain rates. However, these high rates of stress and/or strain will not be combined simultaneously with a thermal shock. Due to the thermal inertia of the concrete, the embedded reinforcing bars, grouted tendons and also the concrete itself will be essentially "warm" during the liquid impact, that is at the temperature of the preceding service condition. Thus, the superposition of extremely low temperature and high rates of

loading is highly improbable. It is only conceivable if a local cold spot had prevailed for a prolonged time before the occurrence of the liquid impulse. Once the dynamic impulse wave has died away the loading condition will correspond to the static LNG-pressure combined with thermal shock.

Besides the case of liquid impact the behaviour of the structural materials and tendon anchorage assemblies must also be known for the dynamic actions of earthquake and explosions of interior or exterior origin. It may be assumed that the relevant temperature of the materials and assemblies corresponds to a normal temperature of 20 °C.

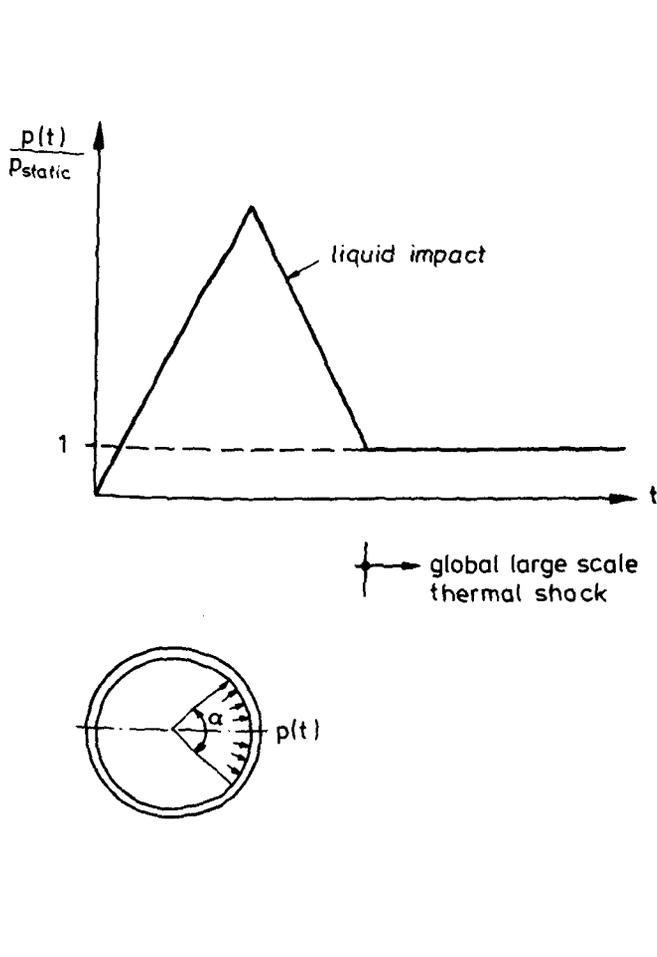


Fig. 6: Liquid impact

3.5 Summary of relevant values

In Table 1 the minimum relevant temperatures for the testing of materials and systems are listed as a summary of the foregoing deliberations.

	structural member	materials and their location	normal service	upon complete rewarming	local thermal shock			liquid impulse		
					T	$\frac{dT}{dt}$	$K \cdot \frac{d\sigma}{dt}$	T	$\frac{dT}{dt}$	$K \cdot \frac{d\sigma}{dt}$
			[°C]	[°C]	[°C]	[K/min]	[-]	[°C]	[K/min]	[-]
p/c-outer tank	p/c-wall and p/c-slab	outer reinforcement	-20 to +40	ambient temperature of climate	-50 to -60	2	stat	as during normal service	0 $\hat{=}$ steady state	dyn
		inner reinforcement	-20 to -40		-170	2	stat			dyn
		tendons and anchorages	-20 to -40		-170	2	stat			dyn
		concrete at inner face	-20 to -40		-170	2 and ∞	stat			dyn
	r/c-dome	outer reinforcement	-20 to +40		irrelevant			irrelevant		
		inner reinforcement	0 to -40		(except possible spill on dome's surface)					
		concrete at inner face	0 to -40							
p/c inner tank	p/c-wall and p/c-slab	reinforcement, tendons and anchorages, concrete	-170	ambient temperature	irrelevant			irrelevant		
			max. $\Delta T \approx 190$ °C for several slow cycles							

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stat - static load rate / dyn - dynamic load rate

Table 1: Relevant values of cryogenic temperature, temperature rate and stress rate for the testing of materials and prestressing systems (ambient temperature for Central Europe) for a p/c-double containment LNG-tank

The values for thermal shock comprise the actions of local or global shock, which must be treated identically with respect to temperature and rate of change of temperature, if the shock spreads slowly. A relevant rate of temperature change of 2 K/min may be assumed, except for sudden shock investigations of concrete. The load rate described by $K d\sigma/dt$ corresponds to static conditions.

The hypothetical load case of liquid impulse due to bursting of the inner tank is connected with a dynamic load rate. During the dynamic load history the temperature of the materials may correspond to the values in regular service. It is, however, also conceivable that, due to a local cold spot prior to the liquid impulse, high loads and low temperatures may be superimposed.

4. TEST METHODS

4.1 Introduction

The assessment of the physical and mechanical properties of structural materials used for the reinforced and prestressed concrete components of RLG-tanks requires test methods suitable for the low temperature. For normal ambient temperature application of concrete, reinforcing bars and prestressing steels the relevant test methods are extensively regulated and described in national standards. Furthermore, many fields are already dealt with today in ISO-Standards, in Euro-norms and others. For low temperature application, there are only preliminary guidelines in a few countries. First information on the state-of-art of low temperature testing was presented in /1/. This section has the aim to actualize the section on testing of /1/ and to present the vital principles of low temperature testing. The test methods presented here should be regarded as possible ways which satisfy the basic requirements.

4.2 Cooling and reheating procedures

4.2.1 On the necessity of temperature control

Irrespective of material, type or size of specimen and type of test, the cooling and reheating of the specimen must be clearly defined and precisely controlled. This is especially important for the experimental verification of thermal and mechanical strains. Elices et al. /14/ have shown that even small deviations of temperature along the specimen's gage length may lead to falsification of the

true behaviour. Clearly, reliable and reproducible results can only then be obtained if temperature control is stringent. Sometimes experimenters have immersed the specimen in liquid nitrogen prior to testing at a required temperature $T > -196 \text{ }^\circ\text{C}$ (LN_2). Subsequently, the specimens were rewarmed at ambient temperature until the envisaged temperature was attained; then the test was performed. A method like this is entirely insufficient to attain reliable results, reflecting the true behaviour of a material.

4.2.2 Function of a cooling chamber

4.2.2.1 Generation and control of temperature

Control and reheating of a specimen should be performed in a cooling chamber. Such chambers are commercially available; they may operate according to different principles. The following description of function has to be regarded as an example.

A commonly used method for generating low temperatures is the utilization of liquid gases, which have been successfully employed as refrigerants in both industrial and scientific fields of refrigeration engineering. This applies, in particular, to liquid nitrogen (LN_2) which is produced and sold on a large scale. With a boiling temperature of the non-inflammable and non-toxic LN_2 of $-196 \text{ }^\circ\text{C}$, more than $30 \text{ }^\circ\text{C}$ lower than that of the LNG, the characteristic values of interest in this context, can be determined with a considerable margin of safety.

LN_2 -operated refrigeration chambers with continuous temperature adjustment work on the principle of regulated injection of defined quantities of LN_2 , which is atomized in the interior around the test specimen and subsequently evaporates. The amount of heat required for this process is withdrawn from the test specimen, resulting in a steady but precisely dosed cooling effect, as the LN_2 -quantity required for maintaining the preselected temperature is injected via a solenoid valve controlled by an electronic temperature controller. By virtue of this control method it is not only possible to obtain and maintain the specified temperatures, but also to carry out controlled cooling procedures following prescribed temperature-time-functions. The heating-up phase included in the temperature cycles can likewise be controlled with a built-in electrical heater when a 3-point-temperature controller suitable for this purpose is installed.

4.2.2.2 Cooling chamber for testing reinforcing bars, prestressing steels, and single unit tendons

Fig. 4.1 gives an example of a cooling chamber which serves for the testing of mechanical values of bars, strands etc. Tensile tests at any given temperature ranging between $+20^{\circ}\text{C}$ and -180°C can be efficiently carried out. The construction consists essentially of a double-walled, heat-insulated chamber whose interior is divided up into three superimposed, separate compartments which can be cooled independently of each other. Because of this division it is possible to cool down the test anchorage device to a lower temperature than that prevailing in the interior test area. Owing to the fact that the strength of steel increases as the temperature is lowered, the test specimens can be made to fail almost exclusively in the test area and not in the area of the test anchorage device because of the notches caused by e.g. the clamping wedges.

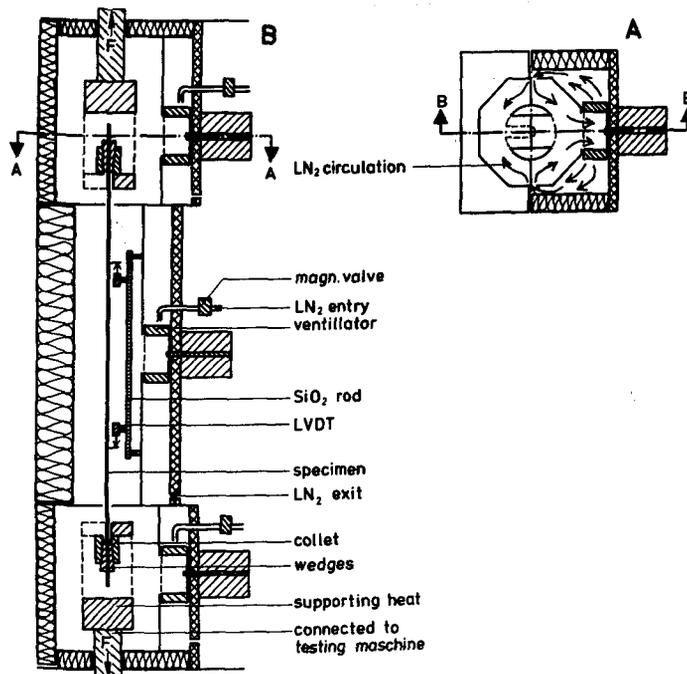


Fig. 4.1: Temperature chamber for tensile testing of steel and single wire tendons (example)

To facilitate access to the interior compartment, the chamber has been designed in such a manner that it can be divided to its full height along its centre line, which is identical with the position of the steel specimen. The removable front part is again divided into three. Thus, each individual compartment is fitted with its own cover. The rear compartment, in which the equipment required for refrigeration generation is housed, has been permanently installed in the tensile testing machine.

The loading-bearing components of all compartments are composed of frames made up of aluminium box sections. Exterior and interior walls consist of bolted-on aluminium sheets of which the spaces were foamed with polyurethane. Aluminium is the predominant material, selected because of its good workability, low weight and rust-resisting property. The last aspect is of particular significance in view of the inevitable formation of condensation on the cold surfaces.

The top and bottom sides of the chamber were furnished with holes through which the tension rods can be pushed. Bushings of cold-resistant plastic material were inserted into the holes to act as sealants.

The layout of the three vertically superimposed interior chambers is of polygonal shape. The smallest chamber diameter of the upper and lower interior compartments measures in each case 230 mm, with a height of 350 mm from top to bottom. Where the anchor block has to travel the specimen's total elongation the chamber diameter is 400 mm. In the interior area, where only the test specimen and the dilatometer had to be accommodated, the diameter was reduced to 150 mm, so as to create no extra space that must be cooled down, in spite of its 650 mm-height. A thin aluminium sheet sufficed as insulation between the individual compartments, as the temperature differences will at most amount to 30 °C. Temperature fluctuations are, in any case, adjusted by the individual control systems.

The manner in which the refrigeration chamber operates is shown in section A-A of Fig. 4.1. A centrifugal fan, driven by an exterior electric motor and rotating behind an opening in the rear interior wall, draws in the gas contained in the chamber, discharges it through the side canals - ending in vertical slits directly behind the separating point to the removable front part - back into the chamber, thus effecting rapid and intense circulation. The temperature controller upon being switched to cooling, opens the solenoid valve installed in the

rear wall. By this process, LN_2 , stored in a dewar, is sprayed into the fan impeller and enters the circulation path reduced to the finest spray. Excess pressure resulting from the drastic volume increase of the evaporating nitrogen can be let off through a borehole in the rear wall. A Pt 100 temperature sensor within the chamber's interior sends off the actual value signal T_k to the temperature controller; one FeCo-thermocouple measures the temperature of the holding jaws the other the steel specimen. A tubular radiator fitted concentrically to the fan impeller with a capacity of 1000 W can effect rapid heating of the circulating gas if required. A cooling system, identical to the one discussed above, is installed in each separate compartment. These devices operate completely independently of one another.

It follows that the temperature control system also consists of three identical control units. The PID-two-point controller must be considered the system's essential component. It records all measured temperatures digitally.

With the control equipment especially designed for this task, extremely sensitive control of the three chamber compartments is possible, with optimal short cooling periods and positive control action in the proportional zone. To obtain short cooling periods by means of undercooling, the LN_2 -valve is kept open for as long as the difference between chamber temperature T_A and temperature of tension blocks T_S is larger than a limiting value ΔT_C . This value can be preselected to range from 5 °C to 15 °C. Only after the temperatures of the specimen and/or the tension blocks have been lowered to approximate to the nominal value and have thus fallen below the threshold ΔT_C , does the controller take over precise temperature regulation and stabilization.

For the purpose of controlling the heating-up procedures, there is a second switching threshold, whose distance ΔT_h can likewise be set between 5 °C and 15 °C and which actuates the heating apparatus in the cooling chamber as soon as the temperature of the holding jaws and/or the specimen has fallen below the momentary nominal value by more than ΔT_h . In this switching condition, the LN_2 -supply is blocked so that the chamber can be brought to room temperature.

The principles of the introduction of force into a specimen will be outlined later on.

4.2.2.3 Cooling chamber for testing of concrete, mortar, and grout

The generation and control of temperature for the testing of concrete or other specimens may follow the same principles as already described in sec. 4.2.2.1. Fig. 4.2 shows as example a cooling chamber, suitable for compression and tension tests. The interior is of a size to accommodate the specimen. Access to the chamber is gained through a door at the front as well as through one hole each in both the bottom and the cover. These holes serve as passages for the compression pieces when testing the compressive strength of cylinders. They may also serve for the introduction of tension rods.

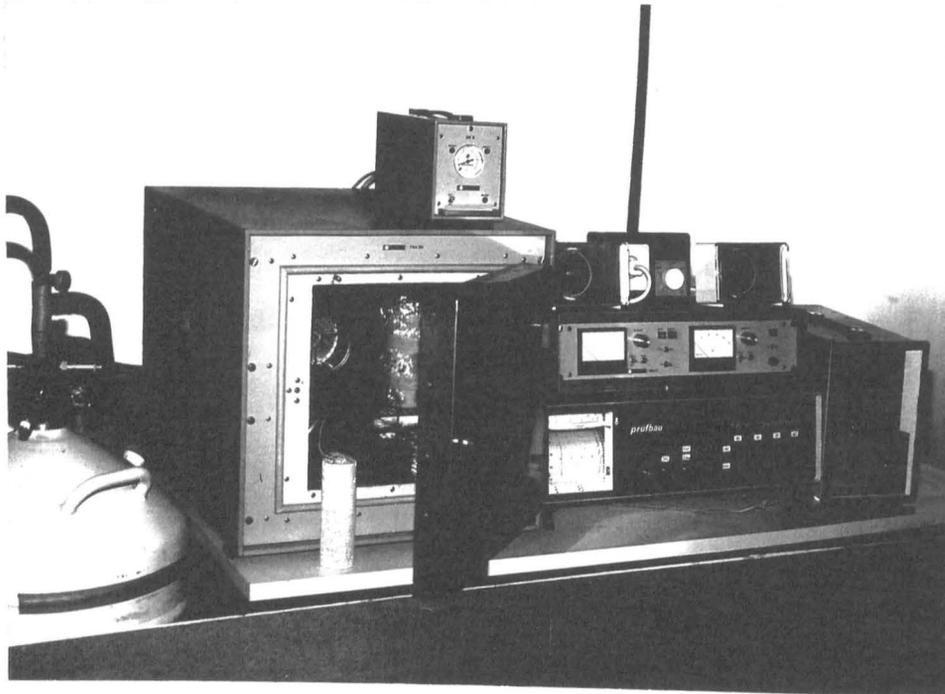


Fig. 4.2: Temperature chamber and units for measurement, programming and controlling the temperature of concrete specimens

The specimen can be cooled directly in the chamber which has been installed in a testing machine. To save time, it is recommended to place specimens which are subjected to temperature cycles prior to the compressive strength test in a second, separately installed cooling chamber and to place the cold specimen immediately before load application into the actual test chamber.

The temperature in the chamber is controlled by a PID-two-point controller that receives the actual-value signal from a Pt-100 sensor installed inside the chamber and actuates the solenoid valve to trigger LN₂ injection. The controller may be linked to a program transmitter to obtain defined temperature curves. For checking the temperature gradients occurring in the specimen it is advisable to measure both the surface and the core temperatures of the concrete specimen with a thermo-couple. In doing so it is not only possible to determine the moment a uniform temperature has established itself over the volume, but also to protect the test material from becoming accidentally damaged through thermal stresses.

Fig. 4.3 shows exemplarily the temperature-time-functions measured in different locations during a temperature cycle. It is advisable to perform a preliminary investigation to assess the temperature differences within the specimen for a certain programmed cooling rate \dot{T}_A of the interior of the chamber. Such investigation will lead to the suitable rates for cooling and rewarming and to the necessary temperature holding time for homogenization. In [1] the relations between the chamber temperature \dot{T}_A , the central temperature T_C and the average temperature T_m were presented. The relations may be applied to demonstrate the influence of the rate of cooling of the chamber temperature \dot{T}_A and of the specimen's diameter on the maximum thermal tensile stress on the surface. We obtain for this stress, which is identical in both circumferential and longitudinal direction

$$\max \sigma = - \dot{T}_A E_c \alpha_T \frac{d^2}{32a} \quad (4.1)$$

with

- \dot{T}_A rate of cooling in K/h
- E_c modulus of elasticity of concrete in tension
- α_T coefficient of linear thermal expansion
- d diameter of cylindrical specimen
- a thermal diffusivity ($a \approx 0.003$ to 0.004 m²/h)

With this equation the rate of cooling may be chosen in such a way that cracking of concrete is reliably obviated. Thermal stresses are smallest in cylinders and unfavourable in cubes. Because of this fact and because of the rotational symmetry of the temperature field, the cylinder is the preferable specimen shape. Naturally, a cooling chamber as described may also be used for the measurement of thermal strains.

As mentioned before, sometimes concrete specimens are suddenly submerged in LN_2 to produce thermal shock. Then, the specimens are tested after complete rewarming at room temperature. The results of the compressive or tensile strength are dependent on the specimen's size; they are of no significant value to describe the behaviour of concrete in the real structure.

The principles of introduction of force into a specimen will be outlined later on.

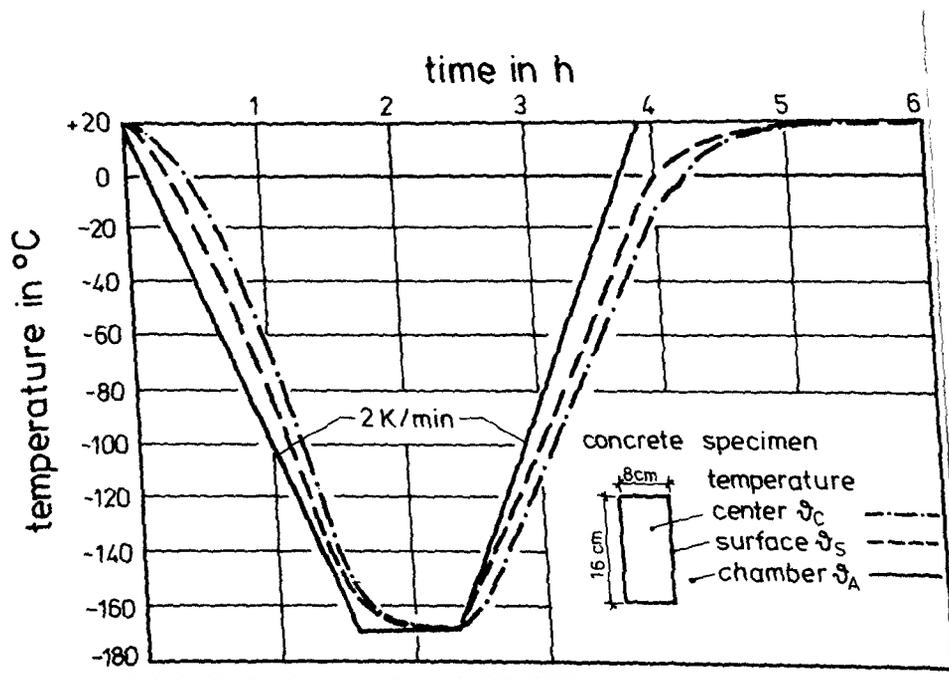


Fig. 4.3: Temperature distribution during temperature cycle

4.3 Assessment of physical properties

4.3.1 Coefficients of heat flow

For analytical studies dealing with the temperature distribution in structural members in the course of cool-down of the inner tank, during cold-spot situations or in the steady state of operation, certain thermal coefficients of the concrete must be known. These are:

- thermal conductivity λ (W/mK)
- specific heat c (J/kgK)
- thermal diffusivity a (m²/h)

Because λ and a are dependent on the moisture of concrete and on temperature - besides other parameters - these coefficients can, for a specific concrete, only be determined by tests.

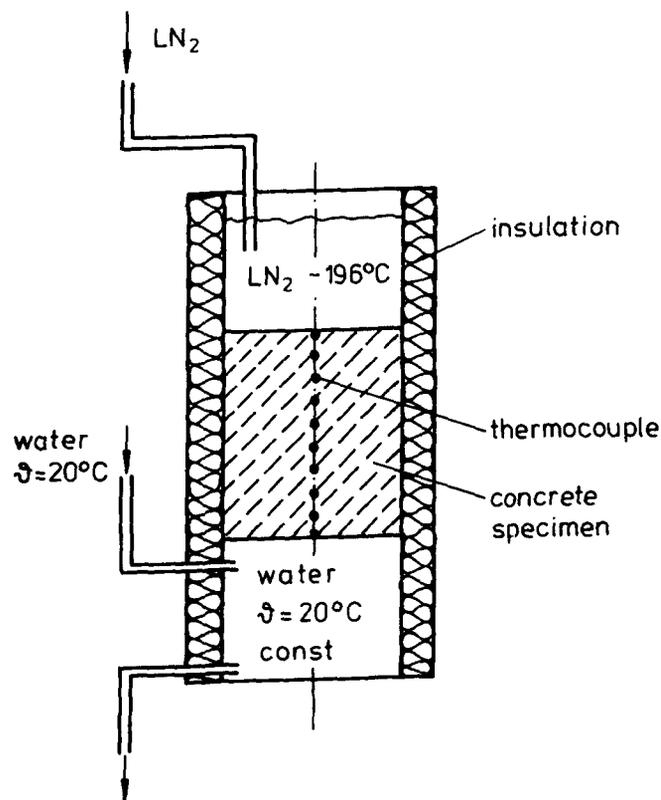


Fig. 4.4: Test set-up for the approximate determination of the thermal diffusivity

Specific heat can be measured by water calorimetry. The thermal conductivity λ should be determined as a function of the moisture content of concrete. Fig. 4.4 shows a simple test set-up for the approximate measurement of the thermal diffusivity

$$a = \frac{\lambda}{c\rho_c}$$

with ρ_c the density of concrete. From a , the coefficient λ may then be derived. As the cylinder of Fig. 4.4 is subjected to unidirectional heat flow, evaluation is performed as follows: the temperature in several locations will be continuously recorded $T(z,t)$. After transformation of the differential equation of heat flow for finite differences stepwise evaluation is performed.

4.3.2 Thermal strain

4.3.2.1 Parameters

Knowledge of the thermal strains of unloaded concrete is important for two reasons. Firstly, the designer needs information on the coefficient of linear thermal expansion α_T to determine thermal movements and stresses. Secondly, from the thermal strain values as a function of temperature conclusions regarding the thermal stability of concrete - subjected to freeze-thaw-cycles - can be drawn.

The thermal strain of a material as derived from a test depends on a series of parameters. The most important are:

- material parameters
 - composition and thermal treatment of steel
 - composition of concrete, mortar or grout
 - maturity, average moisture content of concrete etc., especially free moisture content, density ρ_c
- dimensional parameters
 - diameter and length of specimen
 - ratio 2 volume/total surface = $2V/S$

- temperature-time function
 - T as $T(r,t)$, chamber temperature T_A and its rate \dot{T}_A , and other relevant body temperatures
- thermal parameters
 - λ , c , and a
 - α thermal transition coefficient
- test and measurement parameters

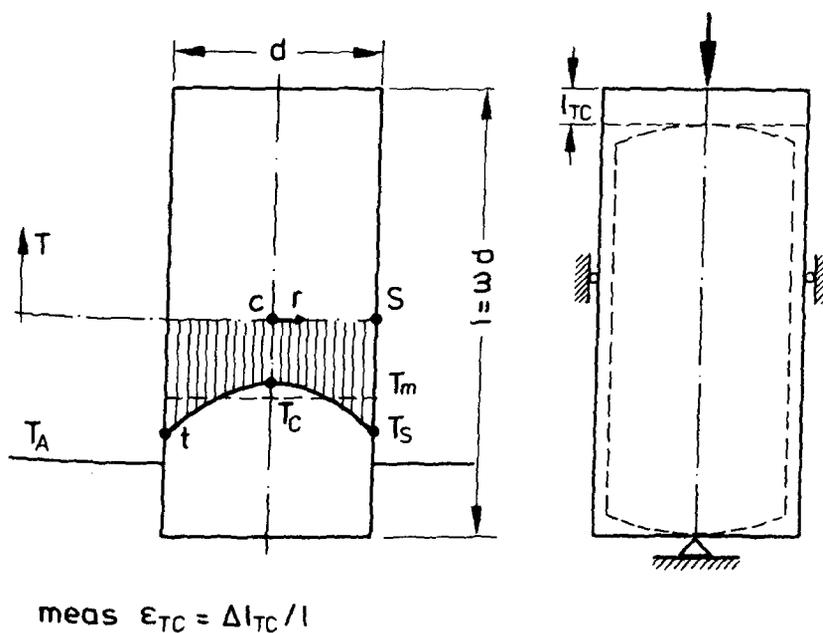


Fig. 4.5: Temperature and deformation of cylindrical specimen during cooling with $\dot{T}_A = \text{const.}$

4.3.2.2 Geometry of specimen

Because the spatial, volumetric thermal strain ϵ_{TV} may be derived from the linear thermal strain of a material, it is justifiable to concentrate firstly on the longitudinal thermal strain. The cylindrical shape is the best geometry because of the rotational symmetry of temperature distribution within the specimen. For specimens made from reinforcing bars and prestressing steel bars, wires or strands in their as-fabricated state, this shape is given beforehand. There is no problem in the fabrication of concrete cylinders, either. The longitudinal thermal strain is usually measured in the body's axis. Fig. 4.5 shows the support condition and the essential notations during cooling.

It is obvious that during cooling or reheating of the specimen with a constant rate of ambient chamber temperature \dot{T}_A , there will exist a non-uniform distribution of temperature. This causes thermal stresses and mechanical strains which may falsify the true thermal strain. The extent of this falsification will be discussed to determine the relevant conditions of test. This discussion will also uncover the influence of the ratio d/l and of \dot{T}_A on the accuracy of the result.

4.3.2.3 Temperature-time histories

The thermal strains of materials for low temperature application are of interest in the range of $+20\text{ }^\circ\text{C}$ to $-170\text{ }^\circ\text{C}$. Furthermore, the thermal strains should be known during cooling and rewarming as well, because hysteretic effects and residual strains may warrant thermal damage of material. Usually, the temperature of the interior of chamber T_A is the guide value for programming and control of a test.

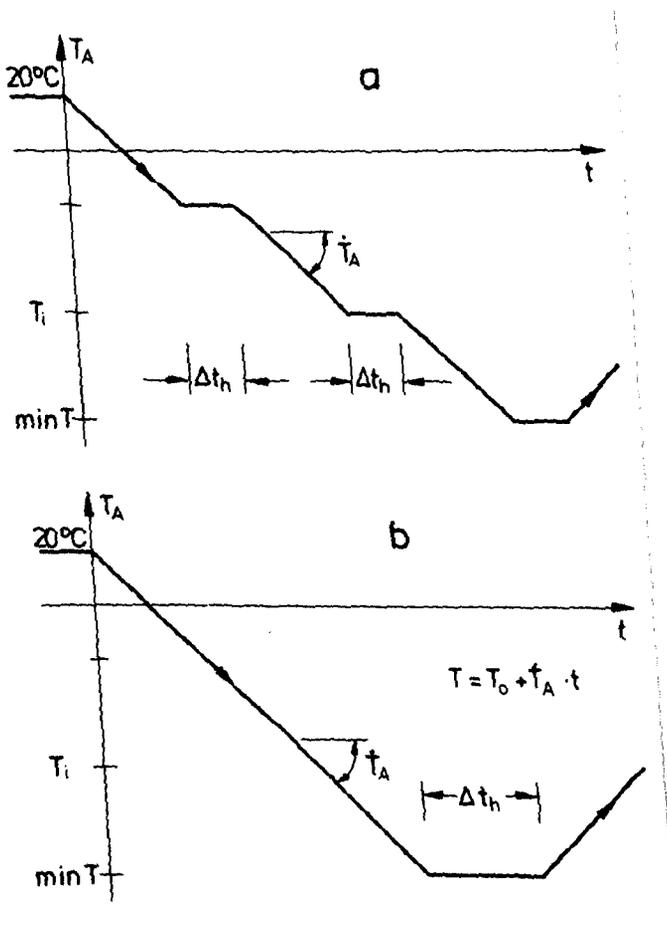


Fig. 4.6: Usual temperature-time histories

Two types of history will be discussed:

a) cooling and rewarming with a constant rate \dot{T}_A during chosen intervals ΔT with homogenization within a holding period Δt_h at each test temperature T_i (Fig. 4.6a).

b) cooling with a constant rate \dot{T}_A to min T without halt, insertion of a holding period, then rewarming to $+ 20$ °C (1 temperature-cycle, possibly repetitive), Fig. 4.6b.

In history (a) at each test temperature T_i the differences of temperature and the thermal stresses will vanish if the homogenization period Δt_h is chosen correspondingly. We will then obtain the true axial thermal strain because

$$T_{Ai} = T_{mi} = T_{si} = T_{ci}$$

History (a) is lengthy and expensive for specimens with increasing diameter and low thermal conductivity. History (b) is usually chosen; however, it is accompanied by a non-uniform temperature distribution and by thermal stresses. It is important to estimate the possible error of strain resulting from these phenomena. This estimation will be based on /1/.

4.3.2.4 Relationships between rate of cooling and characteristic values of temperature

The fundamental relations between the rate of cooling (or rewarming) and certain characteristic body temperatures can be readily derived for the very long cylinder. The influence of geometrical and thermal parameters may also be demonstrated. It was shown in /1/ that for a constant rate of cooling of the chamber temperature, beginning at $t = 0$.

$$T_A = T_0 + \dot{T}_A \cdot t \quad T_0 = 20 \text{ °C} \quad (4.2)$$

the following differences between characteristic temperatures can be derived for a cylinder (Fig. 4.5 and 4.6):

$$\begin{aligned}
 T_A(t) - T_m(t) &= \frac{\dot{T}_A d^2}{32a} \left(1 + \frac{8\lambda}{\alpha d}\right) \\
 T_A(t) - T_C(t) &= \frac{\dot{T}_A d^2}{32a} \left(2 + \frac{8\lambda}{\alpha d}\right) \\
 T_A(t) - T_S(t) &= \frac{\dot{T}_A d^2}{32a} \frac{8\lambda}{\alpha d} \quad (4.3 \text{ a - e}) \\
 T_m(t) - T_C(t) &= \frac{\dot{T}_A d^2}{32a} \\
 T_m(t) - T_S(t) &= -\frac{\dot{T}_A d^2}{32a}
 \end{aligned}$$

with α being the coefficient of thermal transition. For cooling chambers with LN₂-injection α was found to be $\approx 50 \text{ W/m}^2\text{K}$.

Equations (4.3) are independent of time; the time functions of the differences run parallel to $T_A(t)$ according to equ. (4.1). However, these equations are only approximations of the reality: they are valid for the cylinder of infinite length and for the steady state. In reality the differences will become smaller. The time lag, after which parallelity will exist, can be estimated as

$$\Delta t_1 \approx 2 \frac{T_A - T_m}{\dot{T}_A} = \frac{d^2}{16a} \left(1 + \frac{8\lambda}{\alpha d}\right) \quad (4.4)$$

Fig. 4.7 shows schematically the temperature-time lines for certain locations of the cylindrical specimen. These equations can also be applied to other shapes of specimen by replacing the diameter d by an equivalent length l_{equ} :

$$l_{\text{equ}} = 4 \frac{\text{volume}}{\text{surface}} = d_{\text{cyl}}$$

Now, several conclusions can be drawn relevant to the test. Steel and concrete will be compared on the basis of the following values:

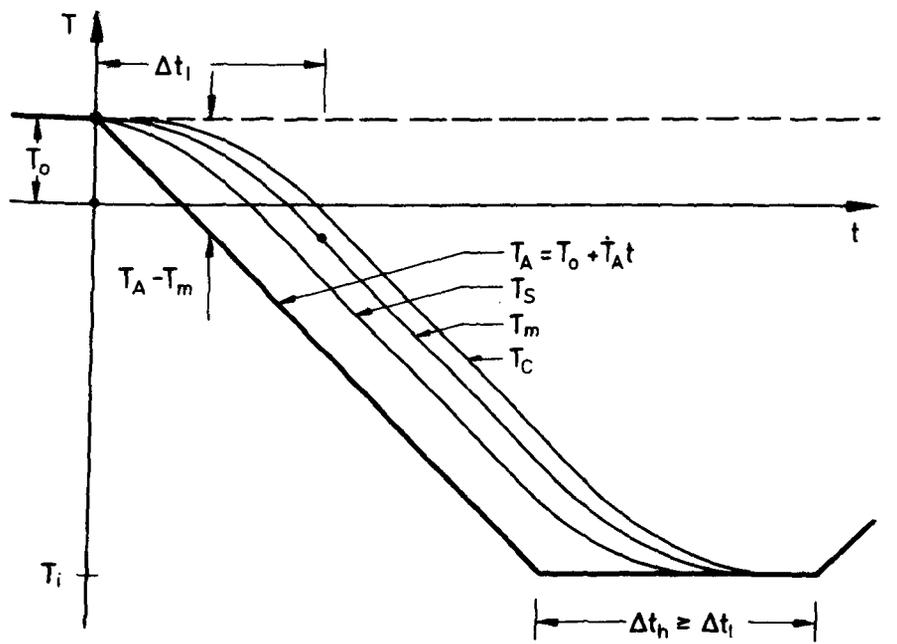


Fig. 4.7: Characteristic temperature functions for the cylindrical specimen

a) steel

$$\lambda = 56 \quad \text{W/mK}$$

$$a = 0.053 \quad \text{m}^2/\text{h}$$

$$d \leq 20 \quad \text{mm}$$

b) concrete

$$\lambda = 2 \quad \text{W/mK}$$

$$a = 0.004 \quad \text{m}^2/\text{h}$$

$$d \leq 150 \quad \text{mm}$$

$$\alpha = 50 \quad \text{W/m}^2\text{K}$$

$$\dot{T}_A \leq 10 \quad \text{K/min} = 600 \quad \text{K/h}$$

Uniformity of temperature across the section

The true axial thermal strain of the material can only be obtained if $T_m - T_C \rightarrow 0$. For steel specimens this requirement is always fulfilled. For a concrete specimen (Fig. 4.8 shows this), the cooling rate must be rather low to maintain a reasonably small difference $T_m - T_C$.

Temperature difference

If temperature control is performed with the chamber temperature as a guiding value then the mean temperature T_m will lag behind T_A . If T_m is not known and the strain plotted against T_A , an erroneous correlation will arise. This error, a shift of temperature, increases with the increase of $T_A - T_m$. For steel this shift is negligible. For concrete it can only then be restricted to $|T_A - T_m| \leq 10$ K, if $d \leq 100$ mm and $|\dot{T}_A| \leq 1$ K/min.

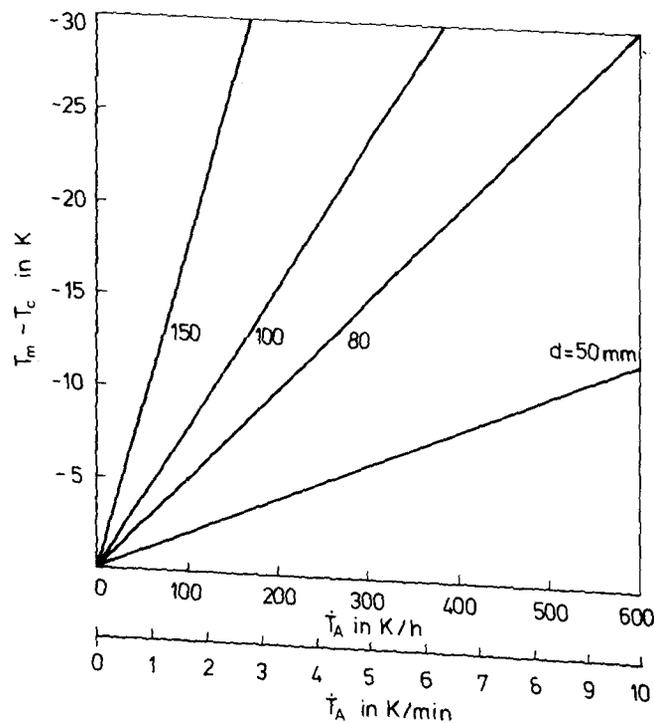


Fig. 4.8: Difference $T_m - T_c$ as a function of diameter of cylindrical specimen and cooling rate

Time lag and halt

The time lag can be estimated from equ. (4.4). The necessary halt Δt_h corresponds to the lag. It can only be restricted by reduction of the diameter of specimen, etc.

Recommendations

- concrete: $d \leq 100$ mm; $\dot{T}_A \leq 1$ K/min
- steel: $d \leq 20$ mm; $\dot{T}_A \leq 5$ K/min

4.3.2.5 Influence of temperature distribution across a section on accuracy of measured thermal strain

In course of cooling (or rewarming) with $\dot{T}_A = \text{const.}$ the measured strain is not exactly the true thermal strain corresponding to the mean temperature T_m (Fig. 4.9):

$$\text{meas } \epsilon_{TC} \neq \epsilon_{TC}$$

This is due to the fact that the end portions of the specimen are St. Venant zones of disturbance which are needed to build up the thermal stresses. We may assume that the length of these regions equals d . The true strain is

$$\epsilon_{TC} = (T_m - T_0) \alpha_T; \quad (4.5)$$

it is assumed to be valid for the inner part $(l - 2d)$ of the specimen, with α_T the linear coefficient of linear thermal expansion (secant modulus between T_0 and T_m). In the two end portions the true strain is supposed to decrease to $\alpha_T \cdot (T_C - T_0)$ because of gradual building up of the eigenstresses. With these assumptions, we arrive at the error contained in the measured thermal strain:

$$\text{meas } \epsilon_{TC} \approx \epsilon_{TC} \left[1 - \frac{d}{l} + \frac{d}{l} \frac{T_C - T_0}{T_m - T_0} \right] = \epsilon_{TC} \left[1 - \frac{d}{l} \frac{T_m - T_C}{T_m - T_0} \right] \quad (4.6)$$

and, finally, at the relative error:

$$\frac{\Delta \epsilon_{TC}}{\epsilon_{TC}} = \frac{d}{l} \frac{\dot{T}_A d^2}{32(T_m - T_0) \alpha} \quad (4.7)$$

For steel specimens this error is minute. For concrete specimens with $d \leq 100$ mm, $\dot{T}_A \leq 1$ K/min and with $l/d \geq 2$ the error may be restricted to less than 5 % of ϵ_{TC} .

4.3.2.6 Influence of temperature variation over the length of specimen

Planas et al. /14/ have shown that a certain, critical variation of temperature along the specimen's reference length may falsify the thermal strain and the mechanical strain of the tensile test. Thus, the temperature and its variation along the reference length must be strictly controlled. Comparative and calibration tests are necessary. The tolerance of ± 1 K or less of the desired test temperature should be maintained.

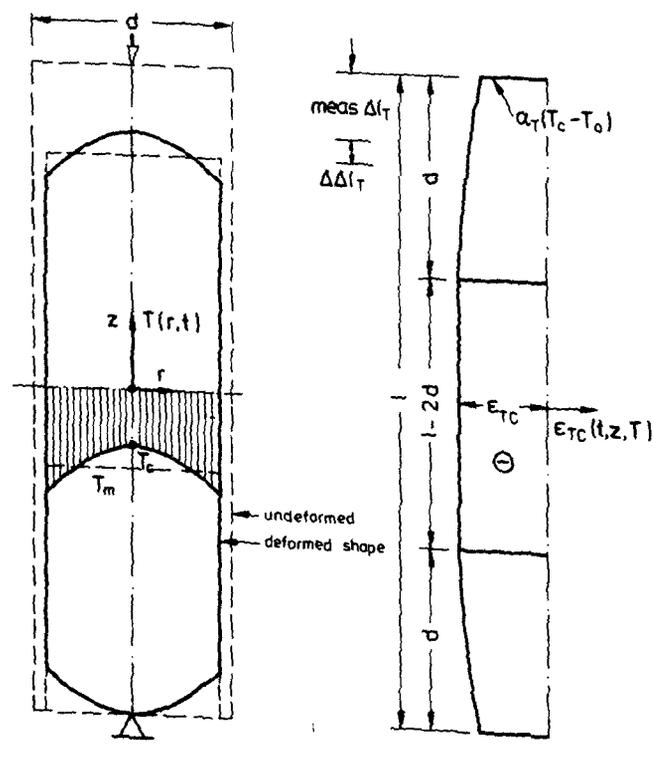


Fig. 4.9: Thermal strain distribution in cylindrical specimen

4.3.2.7 Definitions of α_T

The measurement of thermal strains may have different objectives. The dependence of the thermal strain on temperature for concrete during one complete cycle $+20/-170/+20$ °C is a very reliable indicator as to whether the concrete may suffer frost damage during repetitions of cooling and rewarming /1/. For the calculation of thermal restraint actions the coefficient α_T is necessary. The coefficient α_T may be derived from the measured ϵ_T -T-function as secant coefficient from origin or between adjacent temperatures T_j and T_{j+1} , whichever is needed is determined by the problem to be solved.

4.3.2.8 Other physical effects

Elíces et al. /16/ have shown that the thermal strain is influenced by a simultaneous and constant concrete compressive stress. This observation is valid for moist concrete which exhibits thermal expansion due to frost action.

4.3.3 Measuring techniques

As demonstrated before, the most suitable shape of specimen is the cylinder. Thermal strain is derived from the displacement of the centre points of the end faces Δl_{TC}

$$meas \ \epsilon_{TC} = \frac{\Delta l_{TC}}{l}$$

with l being the length of the cylinder. As to the interpretation of $meas \ \epsilon_{TC}$ in comparison to the true thermal strain and with respect to possible errors, see sec. 4.3.2. It is necessary to measure the thermal strains in the steady state (at the end of a temperature homogenization) and in the transient state during cooling and rewarming as well.

Several techniques have been developed for the measurement of thermal strains. For small size specimens with $d \approx 10$ mm commercial dilatometers are available (cement stone, mortar, steel). Fig. 4.10 shows an example. For concrete specimens special developments are usually necessary.

When measuring temperature-dependent longitudinal changes there is always the problem that each temperature change causes thermal strain not only in the test specimen but in the measuring system as well. This may result in errors in the measured values which can be larger than the strain the specimen undergoes. Though it is possible to determine the behaviour of the measuring system when under thermal strain by carrying out appropriate experiments and adjusting the distorted measured values accordingly, material with the smallest possible coefficients of thermal strain should be chosen for the construction so that the corrections to be made can be kept to a minimum. The most suitable material for the fabrication of a measuring system is SiO_2 -quartz. Besides quartz, certain alloys of very low thermal strain are also available.

Quartz glass whose maximum strain in a temperature range from +20 bis -170 °C lies around - 0.025 ‰ and even returns to zero at lower temperature is a material well suited for this purpose. Taking into consideration the strain measurements to be taken on concrete and steel, amounting to 1 to 3 ‰, corrections of these minor errors can in most cases be omitted. Fig. 4.11 shows a test set-up

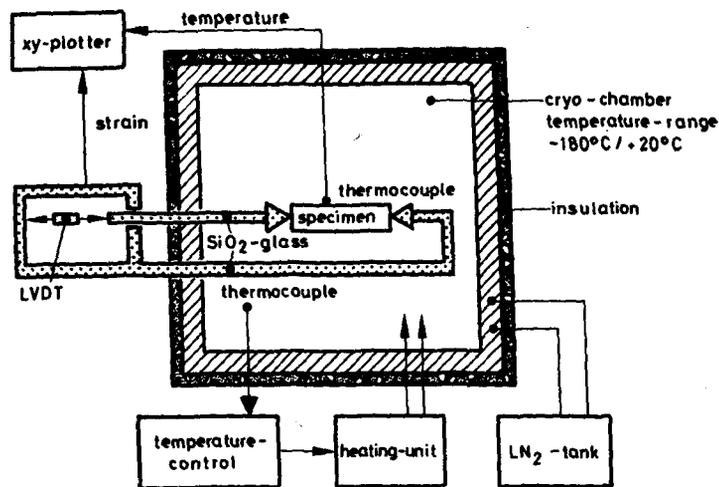


Fig. 4.10: Low temperature dilatometer for small size specimens

using quartz for the frame and for the strain transmitting device. The displacement-transducer system (LVDT), whose performance cannot be influenced by the user, should be installed outside the cooling chamber and be surrounded by a constant temperature.

Proceeding on the considerations elaborated upon above, a strain measuring device can be developed and manufactured of quartz glass to be installed in the cooling chamber. A frame construction in the shape of an equilateral triangle, with a plate fitted in between, serves as a mounting base. Receiving points, always three arranged at an angle of 120° , for specimens of cylindrical shape of \varnothing 80 mm, ensure secure positioning of the test samples. Their varying height is compensated by different heights of the stand-up points. They are clamped at the bottom ends so that they stand up isolated.

Solid quartz rods have been welded vertically into the three corners of the base frame. These rods turn inwards above the test specimen and are fused with the lower end of a thick-walled quartz-glass pipe. This pipe projects through a hole made in the top of the refrigeration chamber to the outside and is fitted at its end, with holding devices for an inductive displacement transducer. The actuator of this transducer asserts pressure on a quartz rod that has been placed concentrically inside the pipe and whose lower end, fashioned to a point, rests on the upper front end surface of a given specimen. In this way, the strain the specimen undergoes is transmitted to the displacement sensors.

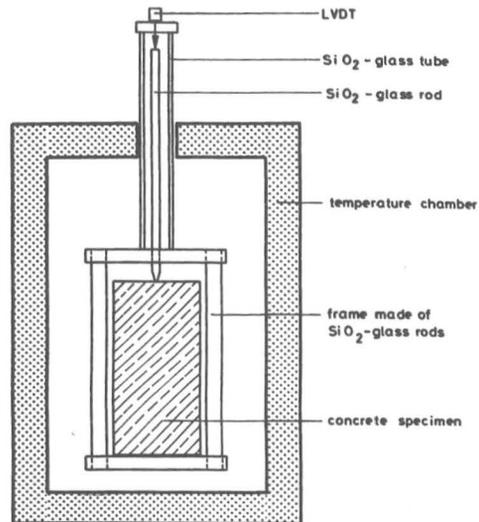


Fig. 4.11: Low temperature dilatometer for concrete specimens

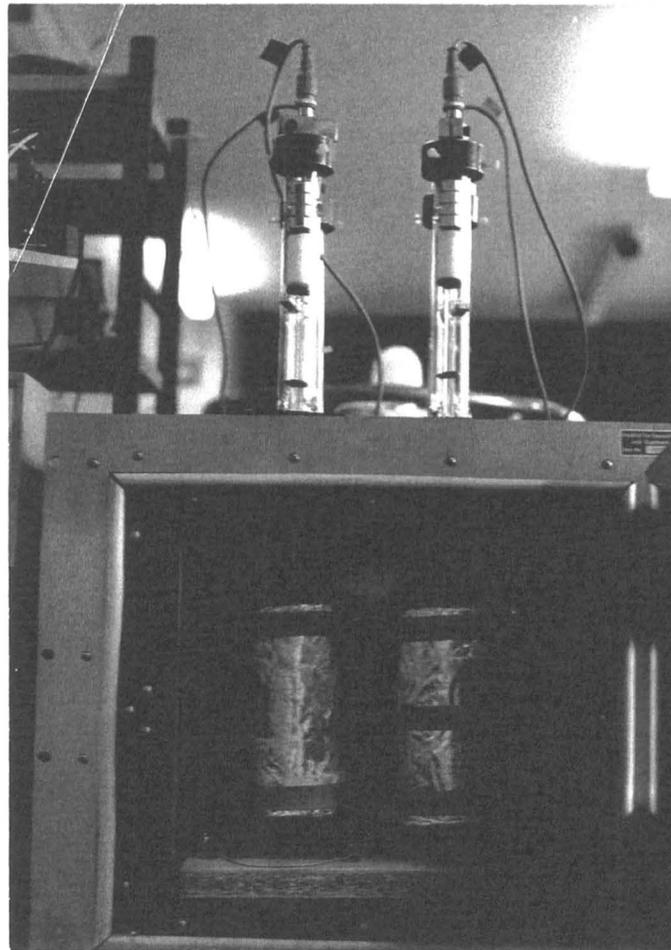


Fig. 4.12: Low temperature dilatometer for multiple testing

Fig. 4.12 shows the photograph of a test set-up for the simultaneous measurement of several specimens.

The recorded strain always constitutes the mean value of the strains experienced by individual volume elements at varying temperature, because of the inevitable temperature gradients in the specimen that occur through the continuous cooling process. To obtain a truly precise ϵ_T -characteristic, the allocated temperature would also need to be taken into consideration as the integral mean value of all participating specimen segments. However, because of the punctiform characteristic of the thermocouple this could be achieved only with numerous measuring points.

When using a single thermocouple, particularly when it is attached to the specimen's surface, a slight displacement of the temperature axis results. The direction of curve reverses at the transition point from cooling to heating-up phase, as the measured temperature value lies first below and then above the mean temperature value allocated to the measured strain.

4.4 Test methods for concrete

4.4.1 Necessary mechanical values for design

In this chapter only such test methods are dealt with as are necessary for the determination of the essential properties for the design calculations for the limit states of service and load carrying capacity, and also of restraint actions. Thus, the testing of the compressive cylinder strength, of the stress-strain diagram in axial compression, of the modulus of elasticity, and of the tensile splitting strength are described here. The compression tests should be strain-rate controlled: $\dot{\epsilon} \approx 10^{-5}/\text{sec}$. The measurement of thermal strain was presented in sec. 4.3.2.

4.4.2 Shape of specimen

Because - even at a very slow cooling-rate - thermal eigenstresses arise in course of the cooling of a specimen (and heating), the cylindrical shape of specimens is best suited for the low temperature testing of mechanical properties. Due to the rotational symmetry of the temperature field, the magnitude of the crack-inducing eigenstresses in a cylinder can be fairly accurately estimated.

Consequently, they can be controlled by the measurement of the temperature on the specimen's surface and in its centre; they can be restricted by the suitable choice of the rate \dot{T}_A . It was shown in sec. 4.3.2.4, how the diameter d of the cylinder and the cooling rate \dot{T}_A of the chamber temperature influence the important temperature differences in the specimen. With equ. 4.3.e the maximum tensile eigenstress on the specimen's surface may be derived:

$$\max \sigma_S \approx \alpha_T E_c \frac{\dot{T}_A d^2}{32 a}$$

Tests have proved that no surface cracking during cooling will occur, if the eigenstress is less than 5 MPa (high strength concrete). This leads to the rule that if

$$\dot{T}_A \cdot d^2 \leq 1.0 \div 1.25 \text{ (Km}^2\text{/h)},$$

cracking can be safely avoided.

In order to obtain representative results that are independent of the effects of random distribution of aggregates on the mechanical properties of concrete, the test specimens should have a diameter five times that of the maximum particle diameter of the aggregate. In conducting compressive strength tests the height/widthratio should amount to at least two to keep the influence of the loaded front ends, which are restricted in their transverse expansion by the pressure pistons with which they come into contact, to a minimum. Proceeding from a maximum particle size of \emptyset 16 mm a body measuring 80 mm in diameter and 160 mm in height and of cylindrical shape is obtained.

4.4.3 Application of force in the axial compression test

The load required in carrying out the compressive strength test is generated by a conventional universal testing machine. The refrigeration chamber is installed between the cross-heads. The load is transmitted to the test specimen via two steel pistons. These pistons are an extension of the pressure plates installed in the machine itself and are pushed into the chamber through holes provided for that purpose (Fig. 4.13). The upper steel piston has been fitted with a connection piece designed as a spherical cup so that the specimen can be uniformly loaded even if its front ends are not exactly in line. When testing cubic specimens, additional steel plates of the size of the cube surfaces are placed between specimen and pressure piston.

The ends of the pressure pistons extending into the chamber have been provided all around with grooves with a view to increasing the surface area and thus thermal contact with the cold N_2 gas. By this means a temperature value only slightly higher than the one recorded for the chamber is achieved on the contact ends of the pistons, irrespective of the considerable heat flow running from the warm to the cooled ends. Beyond that, plates made of highly pressure-resistant, heat-insulating material may be placed between specimen and pressure pistons to preclude changes in the test temperature to the greatest possible extent.

When using the testing machine for compressive strength tests on concrete, it should never be operated at constant stress rate but always at constant strain rate to prevent an immediate closing motion of the pressure pistons at failure of the specimen and so to be able to record the declining branch of the σ - ϵ -characteristic. The load signal required for recording the stress-strain diagram is supplied by a load cell connected to the hydraulic cycle of the testing machine.

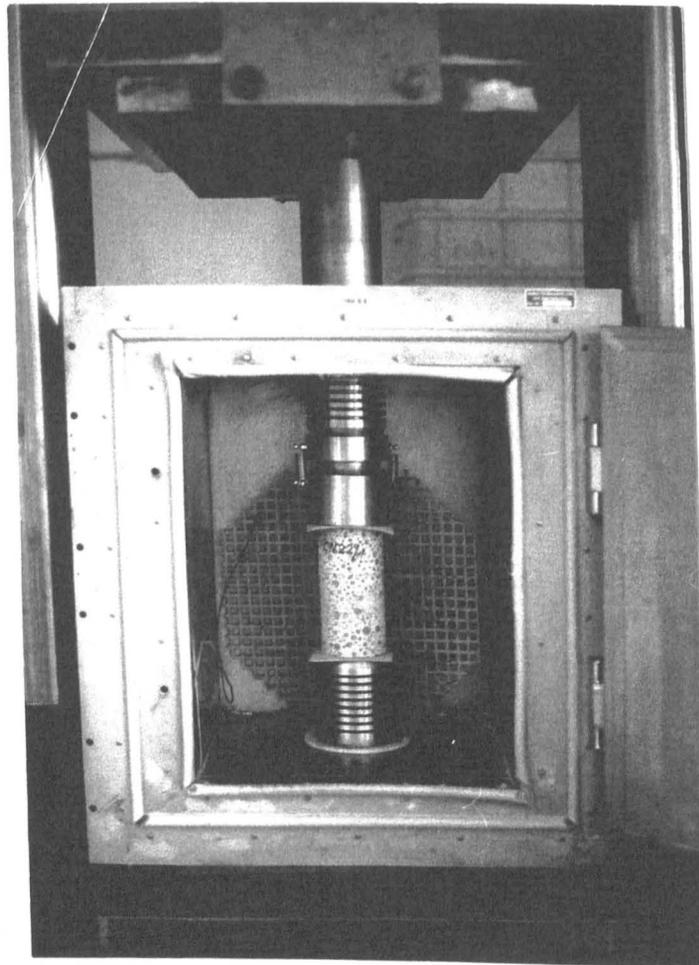


Fig. 4.13: Compression test of Concrete

4.4.4 Determination of load-dependent strain in the axial compression test

For concrete test specimens - contrary to strain measurements conducted on steel - much smaller measuring bases are customary. The clamping devices for inductive displacement sensors would, moreover, turn out to be rather large and difficult to handle on account of the specimen's dimensions, therefore resistance strain gauges (DMS) with a useful lattice length of 60 mm are employed for this purpose. Though adhesive connections in low temperature regions pose some difficulties because of the rough concrete surface, no problems are likely to arise when a suitable adhesive is used. Control measuring carried out with inductive displacement transducers confirm that epoxy-bonded DMS on the specimen are absolutely reliable, even at $-170\text{ }^{\circ}\text{C}$. Usually, 3 DMS at half height and at $120\text{ }^{\circ}\text{C}$ angles are used.

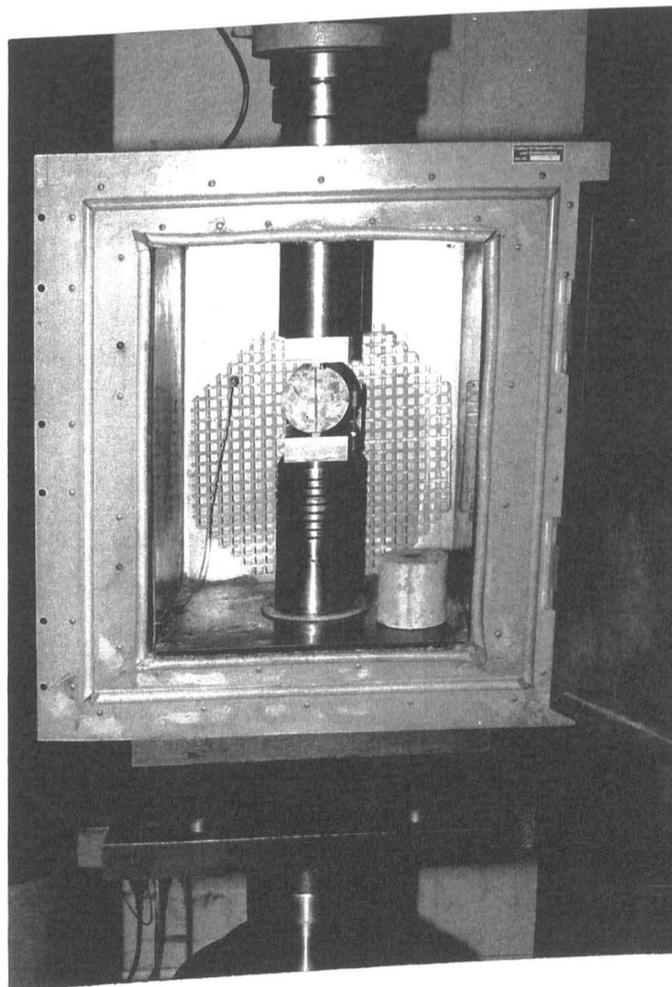


Fig. 4.14: Test set-up of tensile splitting test

When performing a compressive test under isothermal conditions (i.e. at a certain constant cryogenic temperature, after homogenization of specimen), the apparent thermal strain of the wire gauge is unimportant. It can be compensated electrically. It is, nevertheless, advisable to place identically instrumented but unloaded specimens for temperature compensation beside the loaded ones in the chamber.

4.4.5 Tensile splitting test

For the analysis of the limit states of cracking due to load and/or restraint, information on the tensile strength of concrete may be necessary. The tensile splitting test (Brazilian test) is a suitable method for low temperature, owing to its simplicity. Fig. 4.14 shows the test set-up within the cooling chamber. Again, temperature control and complete homogenization are necessary prior to loading. Certainly, the performance of two- or four-point bending tests or of axial tensile tests is possible.

4.4.6 Residual strength after low temperature cycles

In course of maintenance and repair of the LNG-tank, the rewarming of structural members, which have adopted cryogenic temperature during regular service, to normal ambient temperature will occur. This procedure is combined with a cyclic temperature change of about $\Delta T \approx 180 - 190$ K. It was shown in /1/ that temperature cycles may lead to frost destruction if the moisture content of concrete exceeds a certain critical value.

In order to assess the susceptibility of a chosen concrete mix to frost damage, cyclic temperature tests are to be performed on concrete cylinders. The unloaded specimens are subjected to a cyclic temperature history as shown in Fig. 4.6.b. Specimens should be sealed with plastic sheets to preclude drying. Compressive strength and tensile splitting strength are then tested after N complete cycles at room temperature. Thus, the residual strength after temperature cycles dependent on the number of cycles can be determined (sec. 6).

Tests have proved that a lower temperature of $T_u = -80$ °C is sufficient to disclose the concrete's susceptibility to frost damage. Thus, cycling between $+20$ °C and -80 °C is adequate.

4.4.7 Evaluation of results

Evaluation of the cryogenic compressive cylinder strength and of the cryogenic tensile splitting strength as a function of temperature, covering the relevant range, is recommended. Modulus of elasticity can be derived from the stress-strain-lines, which both depend on temperature etc. The temperature-dependent axial compressive strain under the cylinder strength is of interest, because it reveals the embrittlement by low temperature. The requirements will be presented in sec. 6.

4.5 Test methods for reinforcing bars and prestressing steel elements

4.5.1 Standards, properties and definitions

The acceptance and quality control of reinforcement and prestressing steel for the application at normal temperature are connected with a series of test methods and requirements. Both, methods and requirements, are extensively standardized by national and/or international standards. For the testing of the mechanical properties of steel for r/c- and p/c-structural members, the status of international standardization is virtually nil. Nevertheless, it becomes necessary to tie the following proposals for cryogenic testing to such international standards and recommendations, which are generally agreed upon. These standards and recommendations are ISO-standards, Euronorms, RILEM/CEB/FIP Recommendations and FIP Recommendations. They will be cited when needed.

This section deals only with the mechanical properties as gained in the axial static tensile test. Nomenclature and definitions follow ISO/82-1974. The bending-rebending capacity, fatigue strength, weldability and other mechanical and geometrical properties will not be treated. Some of these properties may either change by or at low temperature or they may exert an influence on other properties at low temperature. These latter properties and others are dealt with for reinforcement in the CEB Application Manual on Concrete Reinforcement Technology (1983) and in EU 80 for normal temperature. For prestressing steel EU 138 is relevant, EU types and properties are described in the FIP-Report on Prestressing Steel: 1. Types and properties.

The deformed reinforcing bars, as standardized in, for instance, EU 80 and national standards, are made for structural application at normal temperatures. They are, generally, not suited for cryogenic application beforehand. Their duc-

tility at normal temperature is needed for: a) bending, rebending, and, in case of weldable reinforcement, also for welding, and b) for plastic deformation in the limit states of load carrying capacity. In general, ductility for these tasks is quite sufficient. Low temperatures may reduce the steel's ductility and may change its failure mode from ductile to brittle. This susceptibility for brittle failure increases if the surface of the bar contains notch-like injuries. These injuries may stem from transport, bending, and placing works, and from other sources (scratches, indentations, etc.). Therefore, notched specimens should also be tested (sec. 5.2.4.6). Tests on notched prestressing steel elements are unnecessary, because their notch sensitivity will be disclosed in the tendon-anchorage assembly test (sec. 4.6.3).

Fig. 6.4 shows the schematic stress-strain diagrams of unnotched hot-rolled and coldworked reinforcing bars and the notations of the mechanical properties relevant for design. These notations are also valid for prestressing steels. The properties listed are tested in the so-called isothermal static tensile, i.e. at a certain desired testing temperature after homogenization of the specimen.

4.5.2 Test specimens

The test specimens are principally cut from reinforcing bars and prestressing elements in the as-fabricated condition. It is presupposed that only deformed bars with such a surface geometry (rib pattern, relative area of ribs) are used for cryogenic application which corresponds to the one accepted and/or standardized for normal temperature application (reason: identical bond behaviour at normal temperature).

The free length of specimen between anchorage elements depends also on the dimensions of the cooling chamber. It should be chosen as long as possible, 500 to 1000 mm, depending on the element's diameter. Notch configuration for reinforcing bars is given in sec. 5.2.4.6.

4.5.3 Application of force in the tensile test

The function of the cooling chamber and of the temperature control have already been described in sec. 4.2.2.1. In this chapter, the procedures and measurements of the axial tensile test will be dealt with. The tensile test should be performed in a stiff testing machine of high testing accuracy.

The test specimen and its anchorages on both ends (button heads, wedges etc.) are entirely enclosed by the cooling chamber to ensure a homogeneous temperature distribution along the specimen's length. The anchorages are shoulder-supported within recesses of the so-called holding jaws made of cold-resistant steel. Fig. 4.15 shows such a holding jaw.

The holding jaws are screwed onto the tension rods outside the chamber. The tension rods are then gripped by the clamps or wedges in the cross-heads of the testing machine. The cylindrical ends of the jaws pass through holes in the top and bottom of the cooling chamber. Because the holding jaws can be cooled to a lower temperature than the free length of specimen, breaks in free length can be produced. The isothermal tensile test is performed after complete homogenization of the specimen at the desired testing temperature. Tests should be preferably performed at a constant rate of cross-head displacement: $\dot{\epsilon} = 10^{-5}/\text{sec}$.

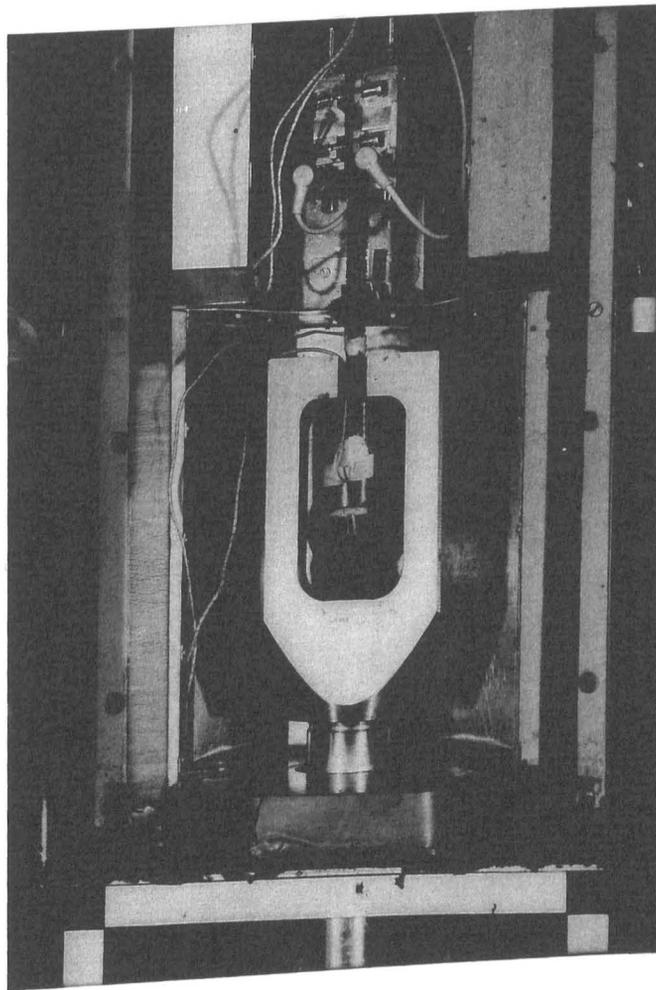


Fig. 4.15: Holding jaw for low temperature testing of steel

4.5.4 Measurement of the load-dependent strain of the tensile test

For measuring the axial strain of the steel specimen inductive displacement transducers should be used rather than electrical resistance wire gauges. The LVDT's have the advantage of better flexibility with regard to measuring base and measuring area. They can be attached without difficulty to specimens of various surface texture with clamps and are not affected by temperatures due to their operating principle. For the low temperature testing equipment several solutions are possible. Two dilatometers are presented here; they differ in some respects quite considerably from one another in their mechanical design.

One of the systems operates with two LVDT's. The transducers are not directly attached to the specimen but have been fitted to a quartz-glass rod on the chamber wall running parallel thereto. Only two relatively light aluminium blocks are clamped to the steel specimen. These blocks are contacted by the activator of the LVDT. Contact with the specimen has been established via two steel blades each and rollers placed on opposite sides. The measuring basis has thus been exactly defined through the distance between the edge pairs (Fig. 4.17).

As the quartz-glass rod to which the transducers have been attached has been pivoted, the entire measuring equipment can be swung away from the test specimen prior to failure of same by means of a cable operated from outside, even if the chamber is closed. Damaging of the measuring system at the time of specimen failure is thus highly improbable as a mechanical contact no longer exists.

Utilization of inductive displacement transducers at low temperature is not without problems. The majority of the devices examined proved to be quite unsuitable for use in the required temperature range. The sensing unit will function satisfactorily if the activator is protected against condensation of water vapour.

When this is not done, the transducer is blocked due to ice formation. The dampness that inevitably befalls the still cold displacement transducers upon completion of each low temperature test must therefore be removed during a storage period of at least two- to three-hours' duration at 60 ... 70 °C before each new test.

Owing to the fact that the arrangement of the displacement transducers permits measuring of the steel specimen strain on one side only, there is a possibility that, if the specimen exhibits a curvature of an order that cannot be neglected, the measuring values obtained are misleading. To avoid such incorrect readings,

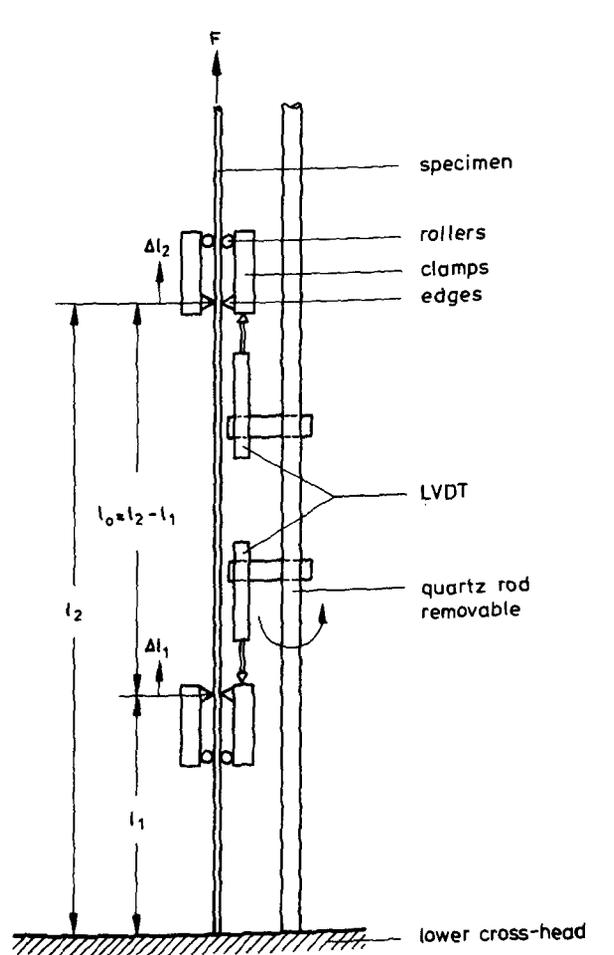


Fig. 4.16: Removable system for strain measurement

a second pair of displacement transducers would have to be installed on the opposite side of the specimen. However, experience has shown that measuring faults due to bent specimens are generally negligible, taking into consideration the close proximity of the specimen axis and measuring systems.

In testing single wires or bars, the danger of the measuring system becoming damaged is much lower than that to be expected with testing strands. For this reason a system can be used that is firmly connected to the specimen so that here, instead of the fragile gauging transducers, inductive displacement transducers with free armatures can be employed (Fig. 4.17). Though this type of equipment cannot be moved away from the specimen during testing, it does have the advantage that there is practically no danger of the transducer getting blocked on account of ice formation, as the core moves about freely in the core canal of the coil housing, requiring no closely restricted mechanical guidance. The steel

specimen is fixed in place with the already described aluminium blocks, fitted with cutters and rollers, which can be attached in pairs. The activators of the LVDT's are coupled with rods made of steel with minute thermal dilatancy. They bridge the measuring base. They experience a thermal strain of a magnitude corresponding approximately to the specimen's. This does not, however, affect measuring precision as only the load-dependent strain is measured at constant temperature. The rods must be protected from the brief temperature fluctuations that occur in the rhythm of the LN₂ feed cycles. This can be accomplished by pushing electro-insulating hoses over them.

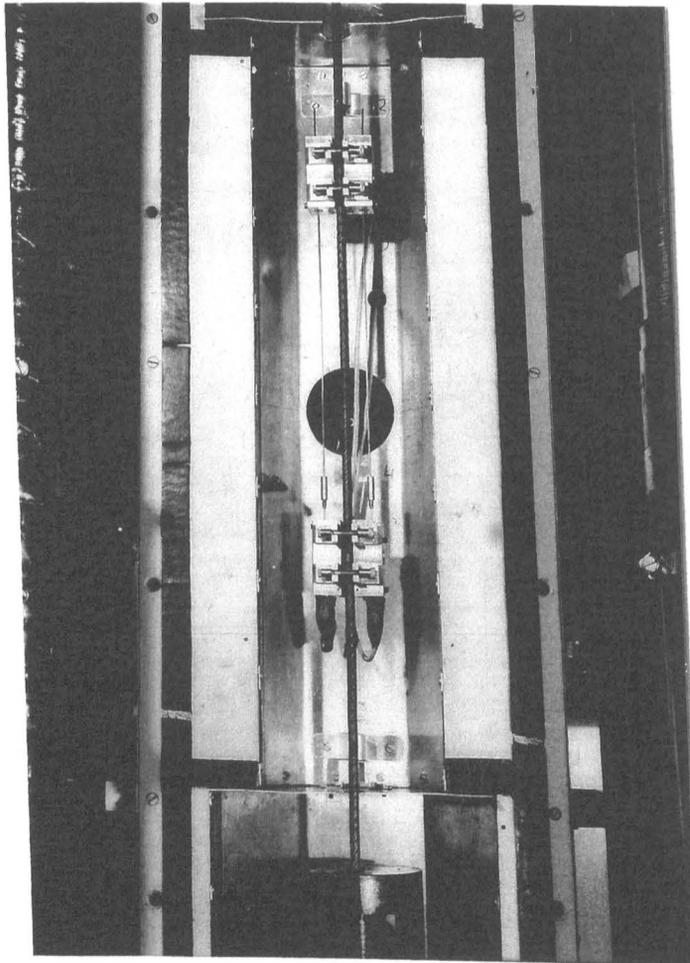


Fig. 4.17: Clamped-on system for strain measurement

By means of two transducers, one placed on each end of the specimen, accurate measuring results can be obtained even on a bent specimen by taking the mean of the two output signals. The mean value is obtained electronically through a dual-channel carrier amplifier. Calibration of the transducers is in each case

conducted inside the cooling chamber at a temperature of around - 170 °C. For this purpose, the displacement of the micrometer spindle of a customarily available calibration device is transmitted over a quartz-glass rod from outside into the chamber interior where it is converted to an electric signal. Thermal sensitivity, however, is fairly low so that only minor adjustments must be made against the calibration carried out at room temperature.

4.5.5 Evaluation of results

Test should be performed within the entire range of relevant temperatures of the material, for instance beginning at + 20 °C up to T_{rel} , with intermediate temperature values (Table 1).

This is necessary to disclose the temperature-dependent change of the mechanical material values of ISO/82-1974: $R_{p0.1}$; $R_{p0.2}$; R_{eu} ; R_{e1} ; R_m ; A_5 ; A_{10} ; A_G and Z (sec. 4.5.1 and 5.2.4.3). The temperature-dependent plot of the stress-strain diagrams is necessary (Fig. 4.15). For notched specimens of reinforcing bars also the notch sensitivity ratio must be determined:

$$N_{sr} = \frac{F_{uN}}{F_u}$$

with F_u and F_{uN} being the fracture loads of the unnotched and notched specimen, respectively. The temperature-dependent change of ductility must be suitably evaluated /1/.

Especially, when testing seven-wire strands, the complete and true stress-strain-diagram is not easy to obtain, but only parts of it: between an initial stress and $\approx R_{p0.2}$. Thus, the machine-diagram of cross-head displacement should be recorded for the determination of A_G (uniform plastic strain at maximum force).

4.5.6 Other properties and tests

It was already mentioned that there are several other mechanical properties of the steel materials, which may become relevant at cryogenic temperature. The relevance depends on: relevant cryogenic temperature, abnormal conditions to be taken into account for in the design (hazard scenarios) etc.

4.6 Test methods for prestressing systems

4.6.1 Introductory remarks

Considering the relatively infrequent need to build LNG tanks, it would be uneconomic to develop prestressing systems only for low temperature application. On the contrary, it should primarily be endeavoured to use approved systems, provided of course, that they prove to be suitable for low temperature application. A promising approach would be to introduce certain modifications of the materials and geometric features of approved anchorages, provided these modifications are still covered by the scope of approval.

It is a known fact that all steels undergo an increase in yield strength and in tensile strength on exposure to low temperature. On the other hand, the toughness characteristics such as elongation at fracture, reduction of area, and notch toughness, progressively decrease, especially in the case of unalloyed and low alloy ferritic and ferritic-pearlitic steels. Some steels exhibit a steep decline of the toughness characteristics below a critical transition temperature. As a result of such steep decline the fracture pattern will change from ductile to brittle /1/.

Irrespective of temperature, brittle fracture must, on account of its disastrous consequences, be avoided in all circumstances. This requirement applies not only to prestressing steel but also to the tendon-anchorage assembly and anchorage zone. Therefore, all the materials involved and their interaction have to be investigated with regard to their suitability for low-temperature application. Within the anchorage the prestressing steel is - depending on the type of anchorage - submitted to high multiaxial stresses possibly combined with notch action. The effect of such embrittling conditions at low temperature has not yet been systematically investigated. Accordingly, criteria for the testing and assessment of prestressing steels and systems under such conditions are still lacking.

For the acceptance procedure of prestressing systems for normal temperature application, most countries have established certain standardized test methods. FIP issued the "Recommendations for application and acceptance of post-tensioning systems" in 1981 /11/. For low temperature application a comparable

proposition for acceptance testing was presented in 1982 at the FIP Congress in Stockholm /17/. In only few countries have tentative recommendations been elaborated up to now. Therefore, there is a strong need to establish test procedures on an international basis.

Acceptance test methods for low temperature application have to be based on /11/ as a guideline. Test methods for the

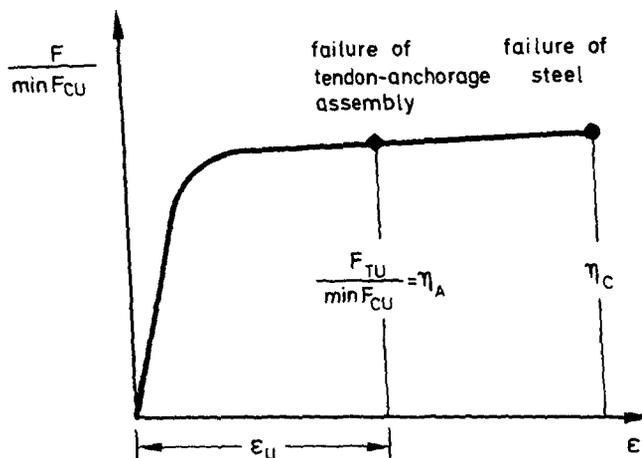
- a) tendon-anchorage assembly of single unit tendons and actual size tendons and for the
- b) anchorage zone

have to be developed accordingly for low temperature.

4.6.2 Definitions and notations

Fig. 4.18 shows schematically the force-total elongation of tendon on free length-diagram of the test according to /11/ for normal temperature. This figure also contains the curve for a low temperature test. the following definitions are used (the subscript p for prestressing steel, as used in the CEB-FIP-Model Code, is omitted):

n	number of steel units per tendon (wire, strand etc.)
A_m	mean cross-section of steel unit
nA_m	total cross-section of tendon
f_{yk}	characteristic 0.2 %-proof stress of steel (yield strength)
f_{ym}	mean yield strength of prestressing steel used for the test
ϵ_{ym}	mean total yield strain of prestressing steel used for test
ϵ_{ym}	$= 0.2 + \frac{f_{ym}}{E}$ [%]
ϵ_u	total ultimate strain of tendon at F_{tu}
F	force of tendon
$\min F_{cu}$	minimum strength of cable without anchorages (subscript c for cable)
F_{tu}	measured strength of tendon-anchorage assembly in test (subscript t for test)
$\max F_{po}$	max. allowable prestressing force including overstressing (CEB-FIP Model Code)
F_{pyk}	characteristic 0.2 %-proof stress times nA_m - characteristic yield force of tendon at normal temperature
F_{pym}	mean 0.2 %-proof stress times nA_m - mean yield force of tendon at normal temperature



- n number of steel units of tendon
 A_m mean cross-section of unit
 f_m mean tensile strength of steel
 $\min F_{CU} = \eta_C n A_m f_m$ minimum cable strength
 F_{TU} measured strength of assembly
 $\eta_A \geq \text{nec } \eta_A = 0,97$
 $\epsilon_U \geq \text{nec } \epsilon_U = 2,3 \%$
- } mode a

Fig. 4.18: Requirements of 1981 edition of FIP /11/

Anchorage efficiency factor and ultimate strain:

$$\eta_A = \frac{F_{tu}}{\min F_{cu}} \geq \text{nec } \eta_A$$

$$\epsilon_u \geq \text{nec } \epsilon_u$$

The requirements, the tendon-anchorage assembly must fulfil for normal temperature application, are listed in /11/; they depend on the mode of sampling of anchorage components. With the subscript T the notations relevant to low temperature are supplemented.

4.6.3 Tendon-anchorage assembly test

4.6.3.1 Test procedure

The test procedure should model the stress conditions of the tendon in the real structure.

Fig. 4.19 shows the test procedure to determine the static strength of the tendon-anchorage assembly:

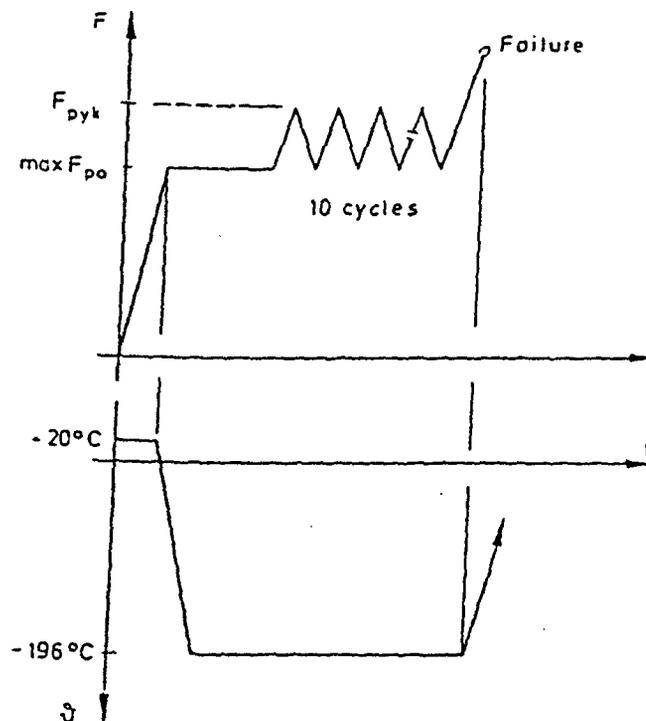


Fig. 4.19: Load sequence for the tensile test of tendon anchorage assembly at low temperatures

- a) The tendon is stressed at room temperature to the maximum allowable force $\max F_{po}$ according to the CEB-FIP Model Code /21/.
- b) Then, the temperature is decreased to the required cryogenic temperature while the force in the tendon is maintained constant (for example liquid nitrogen temperature).
- c) In order to simulate the possible increase in steel stress due to self-stressing effects and to model the stress variation due to several depletions with complete warming-up of the tank, several load cycles between the warm characteristic yield force F_{pyk} of the steel and the allowable force $\max F_{po}$ are executed.
- d) Finally, the tendon anchorage assembly is loaded to failure.

This test procedure can be applied for both single unit-tendon test and for tests with the complete tendon for the sake of comparison also tests at ambient temperature are necessary following the above described procedure. The load cycles at low temperature should disclose the assembly's sensitivity to brittle failure. Depending on the expectable load cases, also other load-time-temperature histories can be included /16/.

The tests with single unit tendons (sec. 5.3) are recommended to study the basic behaviour of the assembly by means of adequate measurements. The testing of complete tendons at low temperature, possibly with a breaking load corresponding to the tendons for the actual work, entails the requirement that all components must attain the test temperature of for instance $-170\text{ }^{\circ}\text{C}$ (Table 1). Thus, this type of test may usually not be performed in a conventional tensile testing machine because the direct support of the anchorages upon the machine's cross-heads will lead to excessive heat losses, and to erroneous results. Temperature control and steady state of temperature become impossible. Therefore, special constructions were developed, Fig. 4.20 shows an example.

For testing cable-type large size tendons the installation shown in Fig. 4.19 may be used. It comprises two similar blocks of concrete, one of which is stressed to the floor of the testing laboratory and the other is mounted movably on rollers. Each block contains a chamber, accessible from above, in which the anchorages are accommodated. These bear against the walls of the respective chambers via steel plates. The tendon is positioned centrally with respect to the two concrete blocks. It is flanked by a pair of hydraulic jacks installed at the same height as the tendon between the blocks. The jacks thrust the blocks apart and thus apply tensile load to the tendon. An appropriate hydraulic control arrangement ensures that the two jacks develop exactly the same amount of travel of their pistons.

The portion of the tendon between the anchorages is enclosed in a metal tube. The chambers in the concrete blocks are lined with insulating material. During the test these chambers and the metal tube are filled with liquid nitrogen, so that the tendon and its anchorages are cooled to $-196\text{ }^{\circ}\text{C}$. By means of solenoid valves and fans installed in the chambers and by atomizing controlled quantities of liquid nitrogen it is also possible to obtain higher test temperatures, i.e., above $-196\text{ }^{\circ}\text{C}$. Experience shows that the anchorage parts and the prestressing steel attain a temperature of $-180\text{ }^{\circ}\text{C}$ to $-185\text{ }^{\circ}\text{C}$ because of heat loss.

Cooling the tendon and the anchorages in the second stage of this program is effected abruptly, i.e., in shock-like manner. This is permissible because the rate of cooling does not exercise an adverse effect (steel has a very high thermal conductivity coefficient; transient thermal stresses do not occur). The load increase in stage (c) is applied only when all the anchorage components and the concrete have been thoroughly cooled; this is monitored with thermocouples.

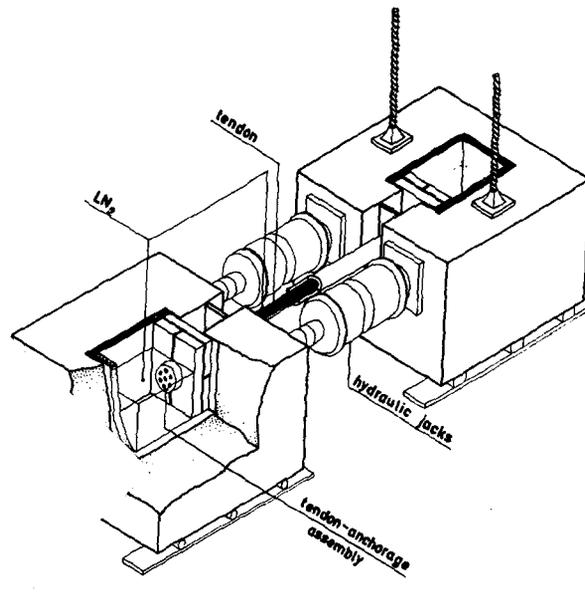


Fig. 4.20: Test set-up for the tensile test of the tendon anchorage assembly at low temperatures

The slow load alterations in stage (c) have the purpose of testing the sensitivity of the prestressing steel - notched by the anchorage elements that grip it - with regard to brittle fracture at low temperature and load variations. This test is therefore a brittleness sensitivity check rather than a direct simulation of loading conditions in the actual structure. It thus pursues aims similar to those of the compressive pulsating load test in accordance with /11/.

Once a prestressed concrete inner tank has been cooled by the admission of liquefied gas, it is normally kept permanently cold in order to minimize thermal restraint effects. Under properly conducted conditions of service the tank is therefore subjected only to minor temperature differences. On the other hand, if the tank is completely emptied and refilled, its temperature will vary within a range of about 180 °C, while the prestressing force remains substantially constant. For this reason tests have been performed on tendons under constant load

and, occasionally, also under constant initial length, which were subjected to just one large range of temperature or to cyclically repeated temperature variation ranges /16/.

4.6.3.2 Observations and measurements

Besides continuous recording of the force and the length of travel of the jacks, it is also possible to measure the strain of the prestressing steel (in the case of wires and bars) with low-temperature strain gauges. Measurement of wire slip and wedge slip at low temperature is very difficult. The relative movement of the prestressing steel and wedges versus anchorage plate can be determined prior and after loading with max F_{p0} and possibly after the test.

The deformations of the anchorage are measured after the test to failure has been performed. The causes of fracture are to be analysed visually and/or with the aid of fractographic methods (e.g., scanning electron microscopy).

4.6.4 Load transfer test

4.6.4.1 Test procedure

In the official certification test for approval of the connection between anchorage and concrete at normal temperature in accordance with /11/ the test has to provide answers to the following questions:

- a) Is the minimum centre-to-centre distance chosen for the anchorages sufficient to ensure that premature compressive failure of the concrete will not occur before failure of the prestressing steel?
- b) Is the splitting tensile reinforcement (end-block reinforcement) adequate in cross-sectional area and arrangement to rule out premature bursting failure of the concrete before failure of the prestressing steel occurs and to ensure that any splitting cracks due to the prestressing force will remain acceptably narrow?

On the assumption that the prestressing system to be tested at low temperature is an officially approved system, these questions will already have been answered in the affirmative in so far as normal temperature is concerned. Now what questions have to be answered under low-temperature conditions?

As the compressive strength of concrete at a temperature of $-170\text{ }^{\circ}\text{C}$ is about twice as high as that at $+20\text{ }^{\circ}\text{C}$, whereas the strength of prestressing steel on cooling to $-170\text{ }^{\circ}\text{C}$ undergoes a much smaller relative increase of only about 20 %, the safety of the concrete with regard to failure in compression is a foregone conclusion.

The question of the widths of the splitting cracks in the concrete at low temperature is irrelevant. The prestress is applied at normal temperature. Low temperature will not cause any cracks that are already present to become wider; the contrary is more likely. What is important is the question whether the splitting tensile reinforcement and the steel anchorage components undergo any appreciable embrittlement due to low temperature.

In respect of geometry, manufacture, etc. the concrete test specimen complies with the requirements stated in /11/. For the test, it is bonded with mortar to the lower plate of the compression testing machine (Fig. 4.21) and its upper part is enclosed in a insulated receptacle which is filled with liquid nitrogen.

For testing the connection between anchorage and concrete at normal temperature in the case of an anchorage with wires individually wedged the force is applied direct to the anchor plate. No attempt is made to obtain realistic transmission of force via the prestressing wires and wedges. At low temperature, however, this simplified approach is not permissible because brittle fracture in the anchorage is liable to occur only in consequence of hoop tensile stresses due to anchorage action. For this reason the force in the low-temperature test is applied - e.g., in the case of a wedge anchorage - to the end faces of short lengths of prestressing steel secured in the anchorage by means of wedges. The end faces of the prestressing steels are ground flat to ensure uniform transmission of the force. The only purpose of the test is to ascertain the behaviour of the anchorage with regard to brittle fracture.

Sequence of cooling and loading follow Fig. 4.19. If the suitability of the anchorage parts and the deformed bar reinforcement was already proved for cryogenic application by other tests, then the load transfer test may be omitted.

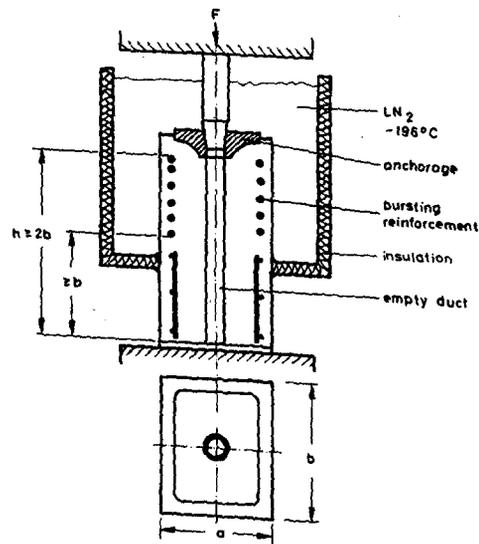


Fig. 4.21: Compression test of the anchorage zone at low temperature .

4.6.4.2 Observation and measurements (see sec. 4.6.3.2 accordingly)

5. ACCEPTANCE AND QUALITY CONTROL OF MATERIALS AND PRESTRESSING SYSTEMS

5.1 Acceptance and quality control of concrete

5.1.1 Acceptance tests for normal temperature and quality control during running production

This section presupposes that prior to actual concreting work on the site the necessary strength classes and the durability requirements of the types of concretes to be used were established. Concrete mix design has to follow the normal procedures for extended inspection. Components of concrete and composition of the mixes chosen for acceptance tests must be identical with the ones for actual execution.

Concrete must meet all the relevant requirements of pertinent standards for normal temperature application with respect to test procedures and necessary properties. During concrete production on site routine quality testing according to relevant standards for normal temperature concrete work must be performed. Changes with respect to materials or composition of concrete require the repetition of acceptance tests for both normal and cryogenic temperature. Quality concrete shall comply with usual standard procedures etc.

5.1.2 Acceptance tests for low temperature application of concrete

5.1.2.1 Fabrication and curing of specimens

Concrete of specimens, cylinders $d = 15 \text{ cm/h} = 30 \text{ cm}$, must be fabricated simultaneously with the specimens for qualification tests for normal temperature with the concrete mix for actual execution. After moist curing under wet burlap for seven days specimens must be wrapped tightly with plastic sheet to avoid drying. Then, they will be stored for 56 days at a climate 20/95; age at testing 56 days. It is recommended to study the effect of the expectable variation of the water cement ratio.

5.1.2.2 Testing of compressive strength and tensile splitting strength at low temperature (LNG)

Temperature values for tests: $+ 20 \text{ }^\circ\text{C}$ and $- 170 \text{ }^\circ\text{C}$. Specimens are to be cooled in a cooling chamber with a rate of 2 K/min to the test temperature. Then, they must be homogenized for 30 minutes prior to test; this is performed in the chamber. At each testing temperature 3 compression tests, 5 tensile splitting tests and 3 tests of the modulus of elasticity shall be performed. With the specimens for the compressive strength also the stress-strain-lines with a strain rate of 10^{-5} s^{-1} must be measured (150 mm base length; three LVDT's on 120° angles). Reserve specimens must be available (sec. 4.4).

5.1.2.3 Testing of compressive and tensile strength after low temperature cycles (residual strength values)

Number of cycles: 5 and 10

Temperature cycle: 20 °C → -170 °C → 20 °C; test at +20 °C after
12 hours of rewarming

Number of specimens: 3 compression cylinders per cycle number
5 splitting cylinders per cycle number

Rate of cooling and heating: 0.5 K/min

Research indicates that cyclic temperatures below - 80 °C do not cause additional frost damage. Thus, a lower temperature of - 80 °C may be chosen if the foregoing statement could be verified by a comparative test.

Cyclic temperature treatment of the specimen, tightly wrapped in plastic sheet, must be performed in the cooling chamber. Testing is performed at ambient temperature. As to fabrication of specimens and their storage, see sec. 5.1.2.1.

With the specimens for the compressive strength also the modulus of elasticity and the stress-strain-lines are to be measured. Residual strength values should be plotted vs. cycles relative to virgin strength. Reserve specimens must be available.

5.1.2.4 Physical values of concrete

Thermal conductivity should be measured on three specimens at + 20 °C and - 170 °C. Thermal-strain-behaviour of 3 specimens should be recorded continuously during 5 cycles between +20/-170/+20 °C etc. Rate of cooling and warming: 0.5 K/min. Type and size of specimens should comply with those of standard testing at normal temperature. Moisture content of specimens must be determined by weighing after drying at + 105 °C.

5.2 Acceptance and quality control of high-strength deformed bars of the inner reinforcement

5.2.1 Definitions

The inner reinforcement of slab, outer wall and inner tank may adopt LNG temperature depending on conditions and loading events (Table 1). This section presupposes that the reinforcement chosen for the actual execution is an electric arcweldable material in accordance with ISO and/or relevant national standards with respect to design strength values, acceptance, and quality control.

Besides such regular steel material, other types of reinforcing bars may be selected provided sufficient experimental data on the mechanical behaviour and experience in production and application are available to prove the equivalence of such material at normal temperature with standard material of a certain required strength class. By such provisions the use of steel material, specially developed for low temperature application, is made possible. Under the same provisions, also, the use of other high-strength deformed steel bars such as prestressing steel bars and the like is made possible.

5.2.2 Sampling of material for the tests

Basis of the sampling are two heats which must be identified by chemical analysis, relevant production data, and mechanical values at normal temperature. From these two heats the steel manufacturer has to fabricate batches of reinforcing bars. The batches must contain bars with the minimum and maximum diameter as will be used in the work. All material must belong to one strength grade. Each batch must contain about 20 bars of at least 12 m length per diameter. Sampling of the bars at the manufacturer's yard will be performed at random by an authorized body. From the sampled bars the gross specimens will be cut and then shipped to the authorized laboratory for testing.

5.2.3 Acceptance tests for normal temperature and routine quality control during production

For material meeting the requirements of relevant standards or of established acceptance criteria for normal temperature application the results of the quality control of the last two years of production must be presented. Additional

qualification tests, performed on specimens from sec. 5.2.2, must be executed to prove compliance of the material from the two heats with the results of the routine quality control.

During production of the reinforcing bars and during execution of work, routine quality control tests at normal temperature must be performed in the same manner and extent as specified by standards.

For other types of reinforcement which are usually not used in r/c- and p/c-construction at normal temperature, the suitability must be established. The results of quality control must be presented.

5.2.4 Acceptance tests for low temperature application of inner reinforcement (deformed bars)

5.2.4.1 Testing temperatures

Mechanical properties must be established at several temperatures to obtain information of the possible transition from ductile to brittle failure. Temperatures: +20°C; -60°C; -130°C, and -170°C.

Specimens for tensile tests are to be cooled within a cooling chamber inserted within the cross-heads of the tensile testing machine. Tests are performed at isothermal condition; cooling rate 2 K/min. Testing temperature must be maintained to ± 2 °C along the entire free measuring length of a specimen. Outer portions of a specimen within clamps or anchorages may be colder than the free measuring length. Temperature record for at least three points within a base length for strain measurement is necessary for each test.

5.2.4.2 Specimens

Tests are performed on specimens with the full section. Free measuring length with the required accuracy of temperature:

$l = 500 \text{ mm}$

Total free length: 1000 mm

Types of specimen: a) unnotched

b) notched at half length. Notch is idented tangentially into body of bar and perpendicular to its axis into the longitudinal rib to a depth of 1 mm into the body excluding the height of rib. Notch shape according to ASTM 370, Charpy V type A (Fig. 5.1)

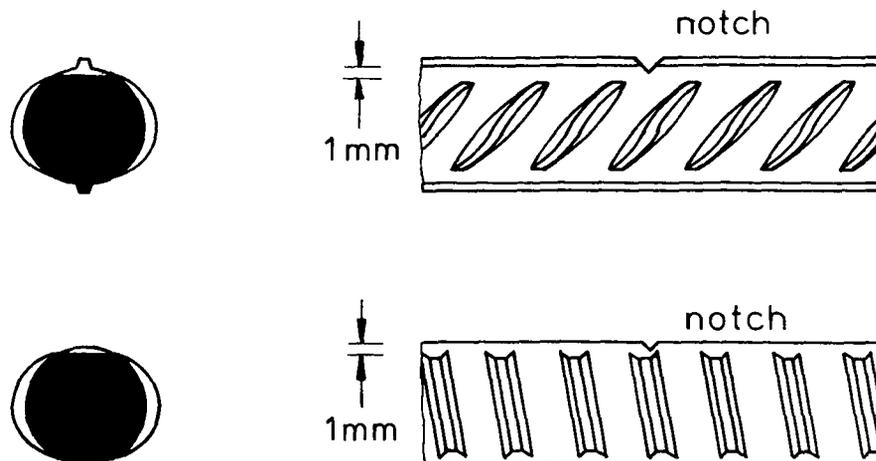


Fig. 5.1: Notch on reinforcement bar

5.2.4.3 Tensile tests on unnotched specimens

Tensile tests at the prescribed temperatures shall be executed according to ISO. The following values must be established:

- stress-strain-diagram up to a strain of 3 %; total machine diagram
- elastic limit $R_{p0.01}$
- yield strength $R_{p0.2}$ and upper and lower values R_{eu} , R_{el}
- tensile strength R_m
- ultimate strains A_5 and A_{10} ; on a 5 times and 10 times diameter basis
- uniform ultimate elongation A_g after failure
- constriction Z

Number of tests: per diameter and temperature 5 tests

Total number: 2 batches x 2 diameters x 4 temperatures x 5 = 80 tests. Reserve specimens must be available. Speed of testing up to yielding: 300 MPa/min; beyond yielding rate of strain should be about 0.05 %/min.

5.2.4.4 Tensile tests on notched specimens

As for sec. 5.2.4.3 microscopic control of notch shape is necessary. The notch-sensitivity ratio must be plotted vs. temperature. Samples are cut from the same bars as for 5.2.4.3.

5.2.4.5 Additional tests

If in actual work bends of bars and welds will occur the suitability of material at low temperature for such treatment must be established in the same manner as for normal temperature.

Coefficient of thermal expansion must be measured. Information as to the type of fracture should be given by fractographic methods.

5.2.4.6 Quality control tests during work

Besides routine quality control by the steel manufacturer further quality control during work must be performed by an independent laboratory. Samples with the said diameters shall be selected from shipments to the site. Numbers of tests according to sec. 5.2.4.3 and 5.2.4.4 per shipment and tonnage must be determined with client's approval.

5.3 Acceptance and quality control of prestressing steel

5.3.1 Definitions

The prestressing steel of the tendons of the inner tank, outer wall and slab may adopt LNG temperature (Table 1). This section presupposes that the types of prestressing steel chosen for the actual execution are materials in accordance with EU 138 or other relevant standards or acceptance regulations for normal temperature use. If for the actual work several types and/or grades of prestressing steel will be used the following requirements are valid for each type and/or grade.

5.3.2 Sampling of material for the tests

All the following requirements are valid for one type of prestressing steel, one grade and one manufacturer. Basis of sampling are two heats which must be identified by chemical analysis, relevant production data, and mechanical values at normal temperature. From these heats the manufacturer has to produce batches of prestressing steel (wire, bar or strand). If from one type and grade of prestressing steel several diameters will be used in the work, the batches must contain the minimum and maximum diameter. A minimum batch weight of 1 tonne should be available. Sampling will be performed at random by an authorized body. The gross samples will then be shipped to the authorized laboratory for testing.

5.3.3 Qualification tests at normal temperature and routine quality control during production

As the prestressing steel is a standardized or accepted material for usual prestressed concrete structures at normal temperature, the results of the quality control of the last two years of production must be presented. Additional qualification tests on specimens - sampled from the batches of sec. 5.3.2 - must be executed to prove compliance of the material from the two heats with the results of the routine quality control.

During production of the prestressing steel to be used for the work the usual routine quality control must be performed in the same manner and extent as specified by standards or acceptance criteria.

5.3.4 Acceptance tests for low temperature application

5.3.4.1 Testing temperatures (as in sec. 5.2.4.1)

5.3.4.2 Specimens

Tests are performed on unnotched specimens with the full section. Free measuring with required accuracy of temperature: 500 mm. Total free length: 1000 mm.

5.3.4.3 Tensile testing

Tensile tests at the prescribed temperatures shall be performed in accordance with ISO. The following values must be established for wires and bars:

- stress-strain-diagram up to a strain of 3 %; total machine diagram
- elastic limit $R_{p0.01}$
- yield strength $R_{p0.2}$ and upper and lower values R_{eu} , R_{el}
- tensile strength R_m
- ultimate strains A_5 and A_{10} ; on a 5 times and 10 times diameter basis
- uniform ultimate elongation A_g after failures
- constriction Z

For strands the strains A_5 and A_{10} shall not be determined. The uniform elongation A_g after failure of specimen may developed from stress-strain-line in combination with the machine diagram. Constriction Z shall be measured on individual wires. Specimens are to be cooled within a cooling chamber inserted between cross-heads of testing machine prior to test; rate of cooling 2 K/min.

Number of tests for one type and/or grade and one diameter per temperature: 5 tests.

Total number: 2 heats x 1 diameter x 4 temperatures x 5 = 40 tests.

Further requirements as in sec. 5.2.4.3.

Further information on the type of failure by fractographic methods shall be presented.

5.3.4.4 Additional tests

If the anchoring of the prestressing force within the anchorage requires the cutting or rolling of threads, the button-heading of wires or other cold-working of the steel, the suitability of the material subjected to such a treatment must be established for low temperature application. These tests can also be performed in connection with the tests on tendon-anchorage assemblies or likewise. Coefficient of thermal expansion must be measured.

5.3.4.5 Quality control tests during work

Besides routine quality control performed by the manufacturer further quality control during work shall be performed by an authorized laboratory. From shipments to the site samples will be selected. Numbers of tests according to sec. 5.3.4.4 must be decided with client's approval.

5.4 Acceptance and quality control of prestressing systems

5.4.1 Definitions

The prestressing tendons and their live and dead anchorages of a p/c-inner tank will certainly adopt the LNG-temperature. The prestressing tendons and their anchorages of the base slab and cylindrical wall of the outer tank may also adopt the LNG-temperature depending on their location within the components of the outer tank. For reasons of safety, prestressing tendons and anchorages must be investigated at the boiling point temperature of the stores RLG (Table 1).

This section presupposes that only such a prestressing system is chosen for the actual work that has already attained acceptance for normal temperature application and for which sufficient experience for regular prestressed concrete work has been gained.

The prestressing steel used for the systems must meet the requirements of sec. 5.3. All data giving information on the mechanical, geometrical, and metallurgical properties of said accepted prestressing system, its acceptance test reports, the acceptance itself, and the data concerning quality control of the anchorage components must be submitted to client in advance.

5.4.2 Acceptance test for low temperature application

5.4.2.1 Low temperature tests on prestressing steel

After qualification and selection of the prestressing steel for the actual work according to sec. 5.3, the mechanical strength values at normal and low temperature have to be established in single unit tests prior to the testing of tendons. Number of samples (sec. 5.3.4.2): 10 samples for each of the testing temperature: + 20 °C and - 170 °C. Tensile tests should be performed according to sec. 5.3.4.3. If the prestressing steel stems from one of the heats and batches, resp., the samples for the tests in sec. 5.3.2 were selected from, the number of single unit tests may be reduced accordingly. The values to be measured are listed in sec. 5.3.4.3.

The single unit tests are necessary for the calculation of the theoretical cable strength of the tendon following /17/. They will be performed in an authorized laboratory.

5.4.2.2 Mechanical and geometrical properties of metallic anchorage components

Anchorage components will be submitted by the prestressing systems producer. Type of sampling of parts should be agreed upon beforehand (random sampling from stock, etc.). All information relevant to composition and thermal treatment of the steel, fabrication, tolerances, mechanical properties etc. should be submitted. If certain modifications of the parts were performed by the systems producer in order to enhance or to attain the low temperature suitability of the anchorage, these modifications should be made known.

On the anchorage types, selected for the tensile tests of the tendon-anchorage assembly, the essential geometrical values should be measured and compared with the data of the acceptance report and of the routine quality control of the system. Surface and body hardness as well as the hardening depth of wedges shall be measured. Similarly, the strength of all other anchorage parts shall be established by suitable methods for + 20 °C and - 170°C. Tests are to be performed by an authorized laboratory which decides upon the type, number and program of necessary tests.

5.4.2.3 Tensile tests on single unit tendons

If the tendons for the actual work consist of several wires, bars or strands individually anchored within one compact anchorage, tensile tests on single unit tendon have proved to be essential. This is due to the fact that in low temperature tests on actual size tendons the measurement of the elongation along the free length of tendon and of the slip of wedges or other relative displacements is extremely difficult and inaccurate at the same time. However, in tests on single unit tendons these values can be established reliably.

A specimen consists of a single prestressing steel unit anchored at both ends as in the real anchorage. This laboratory anchorage is either a regular single unit anchorage of the system or fabricated from a regular anchorage or fabricated for the purpose of these tests. Certainly, essential properties must be identical with the anchorages for the work.

Tests are performed in a cooling chamber inserted between the cross-heads of the tensile testing machine. The entire unit tendon, prestressing steel plus anchorages, is subjected to the testing temperature: + 20 °C and - 170 °C. Tempe-

temperature control along the free length of tendon and of the anchorages is essential. The temperature in any location should not deviate by more than ± 2 K from the testing temperature.

Free length of tendon should be 1000 mm; elongation of steel should be measured along the inner 500 mm (base length) with LVDTs and other equipment suitable for low temperature strain measurement (low and quantifiable temperature dependent apparent strain). Transfer of displacement from interior to exterior is not recommended.

Specimen is mounted in the chamber and connected to the tensile testing machine at $+ 20$ °C and then loaded with a low initial load. The anchorages are shoulder-supported within the chamber by auxiliary tensile members protruding into chamber and fastened to the machine clamps etc. After initial readings of strain and relative positions of steel versus anchorage parts, cooling is performed according to sec. 5.2.4.1. Fig. 4.1 gives an example for the test set-up.

Test procedure follows sec. 5.4.2.4.

The following data should be recorded: elongation along free length vs. load, ultimate load, constriction, final slip of wedges etc., force-elongation curve from machine diagram. Because of the possible damage to the strain measuring system the latter should be removed well before breakage, however beyond a load corresponding to the 0.2 %-proof stress of the prestressing steel.

The recorded values should be compared with the relevant values of the prestressing steel without anchorages. The anchorage efficiency factor according to /11/ shall be calculated for subsequent comparison with the results of tendon-anchorage assembly tests.

5.4.2.4 Acceptance tests on the tendon-anchorage assembly

Fabrication of test specimens

Tensile tests on tendon-anchorage assemblies shall be performed in an authorized laboratory. They may also be executed at the facilities of the producer of the system or elsewhere, provided the tests are supervised by officials of the authorized laboratory. Tests should be performed with the largest type of tendon used for the actual work. If, however, the breaking strength of such type of

tendon exceeds the capacity of the facilities of the laboratory etc., tests may be performed on a smaller-size type of tendon. However, similitude of the anchorage chosen for the test with the anchorages for the work must be ascertained.

The test specimens should have a free length of ≥ 2.50 m between anchorages. Support of anchorages must comply with the real one. The test tendon may either have live anchors on both ends or on one end a live anchor and on the other end a dead anchor. If the dead anchor is an anchorage by bond, this must be included in the test. The prestressing steel should be identical with that of the tests carried out according to sections 5.3 and 5.4.2.3. Test tendons should be assembled at the laboratory by the personnel of the systems producer under the supervision of laboratory officials.

Test procedure and measurements

As to the procedure of the tensile test, see sec. 4.6.3. Temperature should be measured in several locations by thermocouples. Test is performed in liquid nitrogen, unless the laboratory has the facility to test the complete assembly at -170 °C under homogeneous, isothermal condition.

Besides the load, the total elongation of the specimen derived from the machine diagram (cross-head displacements) and the total slip of wedges and other relative displacements should be recorded.

Three tendon-anchorage assemblies should be tested at $+ 20$ °C and at $- 196$ °C each.

Evaluation of data

In connection with the tests of sec. 5.3 the theoretical values of the cable strength as a function of temperature and the anchorage efficiency factors should be determined. Mode of fracture and the total elongation should be assessed. Evaluation shall be presented in a comprehensive test report written by the authorized laboratory.

5.4.2.5 Acceptance tests on anchorage zone

They are to be performed according to sec. 5.4.2.4 and 4.6.4. Quality assurance tests are not needed. Identity of the metallic anchorage components used on site with those tested must be certified.

If the cryogenic suitability of all metallic anchorage components and of the deformed bar reinforcement of the anchorage zone was established by other tests, the tests in sec. 5.4.2.5 may be omitted.

5.4.2.6 Quality control

Quality control of all components of the tendons and the tendon fabrication shall be in accordance with the recommendations of /11/. Producer of anchorage parts must certify the compliance of properties of the parts delivered to site with those for the qualification tests.

6. REQUIREMENTS FOR MATERIALS AND PRESTRESSING SYSTEMS FOR CRYOGENIC APPLICATION

6.1 Scope

Tank structures for the storage of RLG are planned and built following widely differing design concepts. These concepts are again combined with differing load conditions. Certain requirements regarding performance, protection and reparability must be fulfilled. These functional requirements, load conditions etc. are not internationally standardized, though some national specifications already exist. Normally the specification for the individual job is the subject of mutual agreement by the parties involved.

This fact leads to the conclusion that the formulation of a rigid set of requirements for materials and systems is neither possible nor reasonable. Nevertheless, one basic requirement must always be fulfilled: brittle failure of structural components of a liquid-containing or protective structure must be precluded in all circumstances, irrespective of the origin of actions and independent of prevailing temperature and strain rate. All subsequent remarks centre on this demand.

For a composite material such as prestressed and reinforced concrete this requirement can be met if the steel materials involved exhibit a sufficient ductile behaviour, i.e. plastic elongation prior to failure. Concrete in compression tends to embrittlement with decreasing temperatures. However, the toughness of a prestressed concrete member does not solely depend on the ductility of one of the materials, but on all materials forming the composite "p/c + r/c". Toughness

of a p/c-section or r/c-member is the total deformational work, especially the plastic portion thereof, available for consumption in a particular limit state. Certainly, toughness depends mainly on the steel's ductility. The contribution of concrete is small, already at normal temperature. These remarks underline the importance of the above-mentioned basic requirement.

The subsequent requirements are based on the conditions presented in sec. 3. Thus, they have an exemplary character as being related to the design features and materials of Fig. 1 and Table 1. The main purpose of these requirements is the instigation to criticism and to improvement.

6.2 Requirements for structural concrete

6.2.1 Strength and deformation at cryogenic temperature

Fig. 6.1 schematically shows the temperature-dependent alteration of the stress-strain line of concrete in axial compression, of the cylinder compressive strength, and of the axial compressive strain ϵ_{uT} . No strength requirement is presented here. If the analysis of the structure requires the modelling of the temperature-dependent mechanical behaviour of concrete, the stress-strain-lines covering the entire range of low temperature must be known /22/.

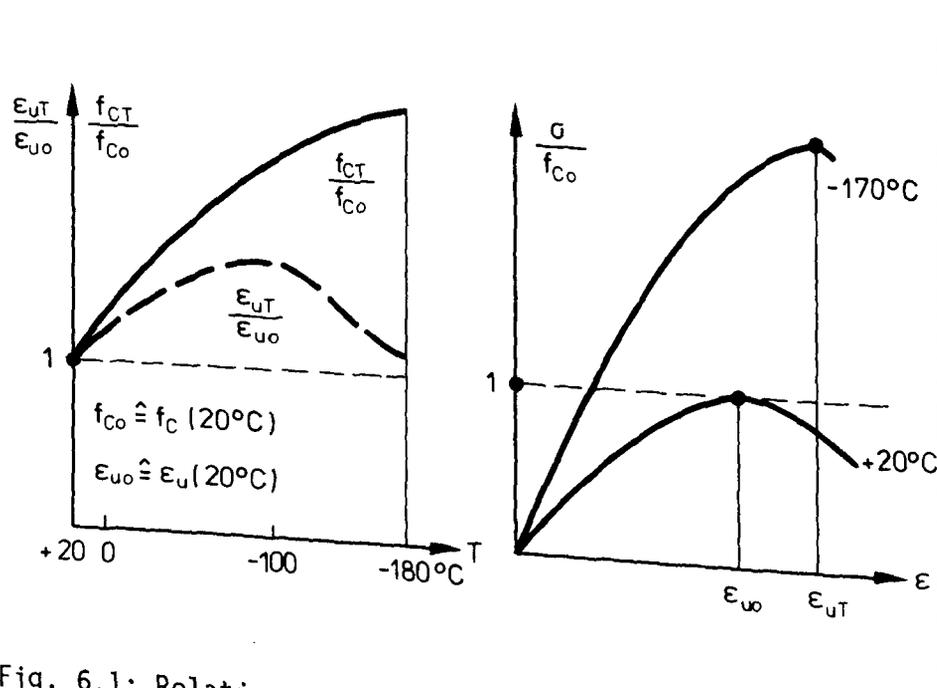


Fig. 6.1: Relative compressive cylinder strength f_c and strain ϵ_u of concrete vs. temperature. Stress-strain-lines in axial compression at isothermal condition

To ensure adequate ductility of the prestressed and reinforced cross-section at the limit states of load-carrying capacity, the axial compressive strain should not be affected by low temperature:

6.2.2 Residual strength after temperature cycles

Fig. 6.2 shows the possible diminution of strength by thermal cycles. The following requirements should be fulfilled after 10 cycles:

$$\frac{f_{cT}}{f_{co}} \geq 0.90$$

$$\frac{f_{tsT}}{f_{tso}} \geq 0.90$$

with f_{cT} and f_{tsT} being the residual values of the cylinder compressive strength and of the cylinder tensile splitting strength, respectively, after $N = 10$ cycles. Fig. 6.3 shows the temperature history for this test, and Fig. 6.2 depicts in its right half the thermal cyclic strain whose measurement can be combined with the tests of the residual strength.

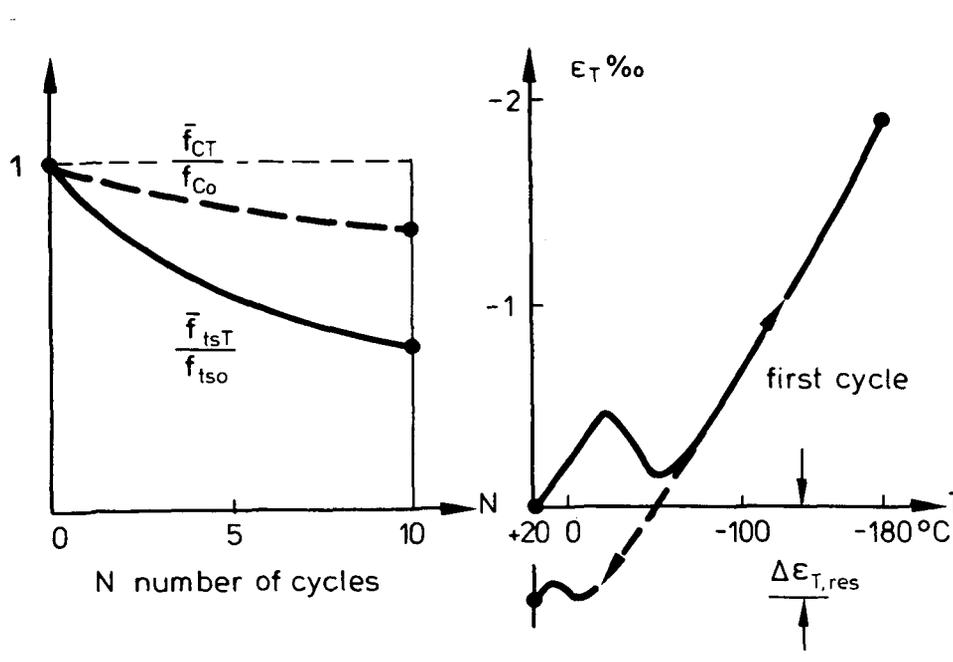


Fig. 6.2: Residual strength of concrete after thermal cycles and cyclic thermal strains

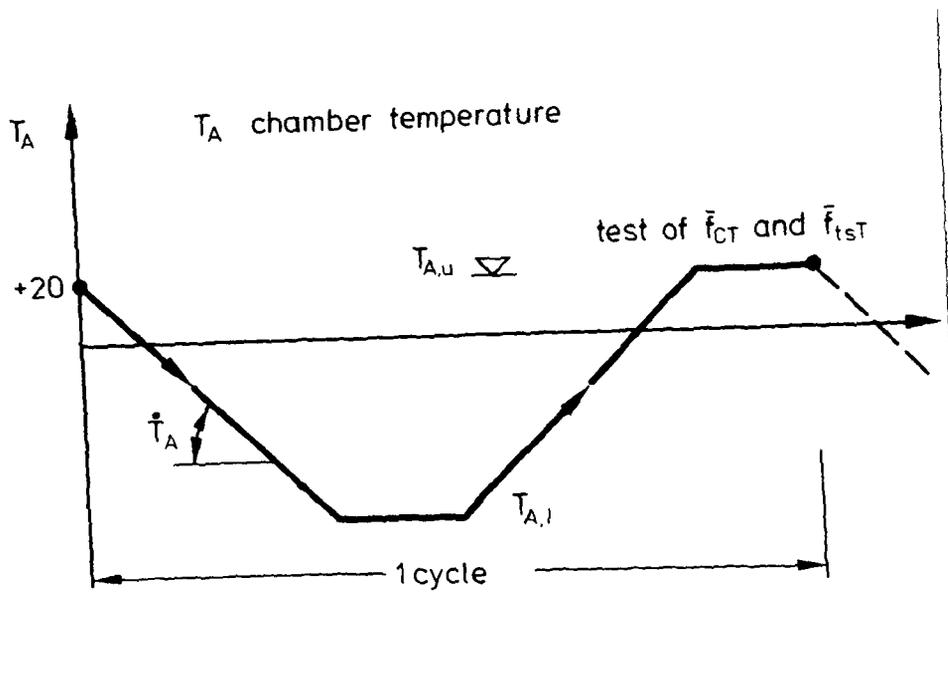


Fig. 6.3: Temperature cycle for determination of residual strength of concrete

6.3 Requirements for reinforcement

6.3.1 Role of reinforcement

For the design concept as shown by Fig. 1 (double containment vessel), for the loads, strain rates, and relevant temperatures as presented in Table 1 and sec. 3, the reinforcement must contribute to the structural integrity (load carrying capacity) and to the fluid- and gas-tightness of the system.

The contribution of the reinforcement to the structural resistance of a p/c-member, subjected to static or dynamic actions and to normal or cryogenic temperatures, requires a certain amount of plastic deformability prior to the breaking of a bar. This statement is also valid, if the increase of yield strength of the steel due to low temperature is not utilized in the limit state design, because the response of a structural member at low temperature will be a function of the real stress-strain behaviour of materials and not of a conservatively adopted one, e.g. valid for + 20 °C. This fact becomes especially evident in case of a local or global thermal shock. Then, the restraint forces certainly depend on the true temperature-dependent material laws, and on the temperature-dependent stiffness of the members.

The reinforcement must also contribute to the tightness of the tank. The release of RLG in the gaseous and/or liquid phase to the environment is combined with the hazard of a gas cloud explosion; such release has to be precluded. Tightness of the inner and outer tank can be achieved by a sufficient amount of cryogenic reinforcement placed at the member's cold surfaces. Then, the crack width can be controlled in such a way, that a limit value w_k is not transgressed. By this measure, also the strain of liner due to thermal restraint is controlled. Furthermore, a minimum value of depth of the compression zone of the members to maintain tightness can be ensured by the amount of steel and by the magnitude of prestress.

6.3.2 Ductility requirement

Fig. 6.4 depicts the schematic stress-strain-lines for two types of rebar and also the denominations of ISO/82, which will be used further-on. In Fig. 6.5 the known fact is shown that both yield strength and tensile strength of rebars increase as the temperature decreases. As strength increases, all the other mechanical values describing the steel's ductility are diminished by low temperature.

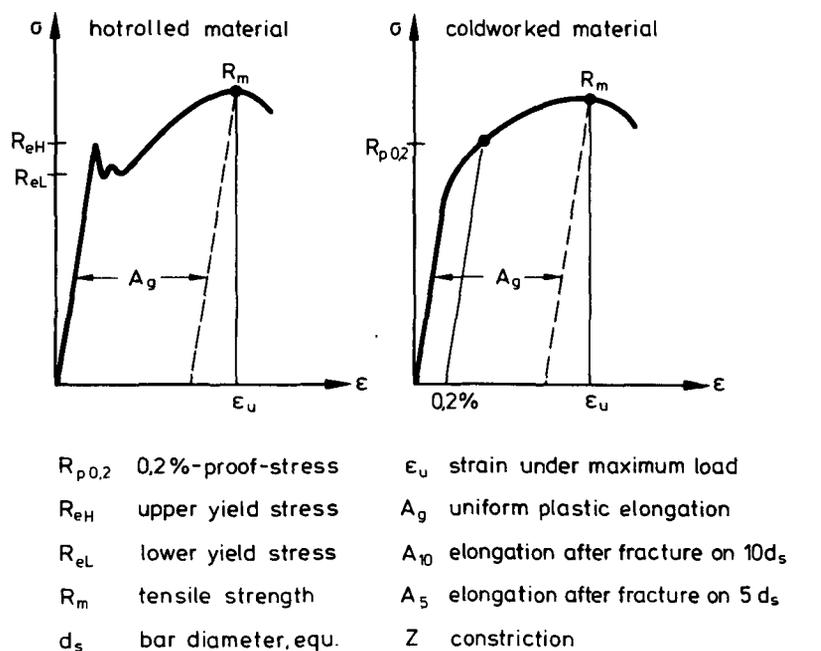


Fig. 6.4: Schematic stress strain diagrams and notations for deformed reinforcing bars

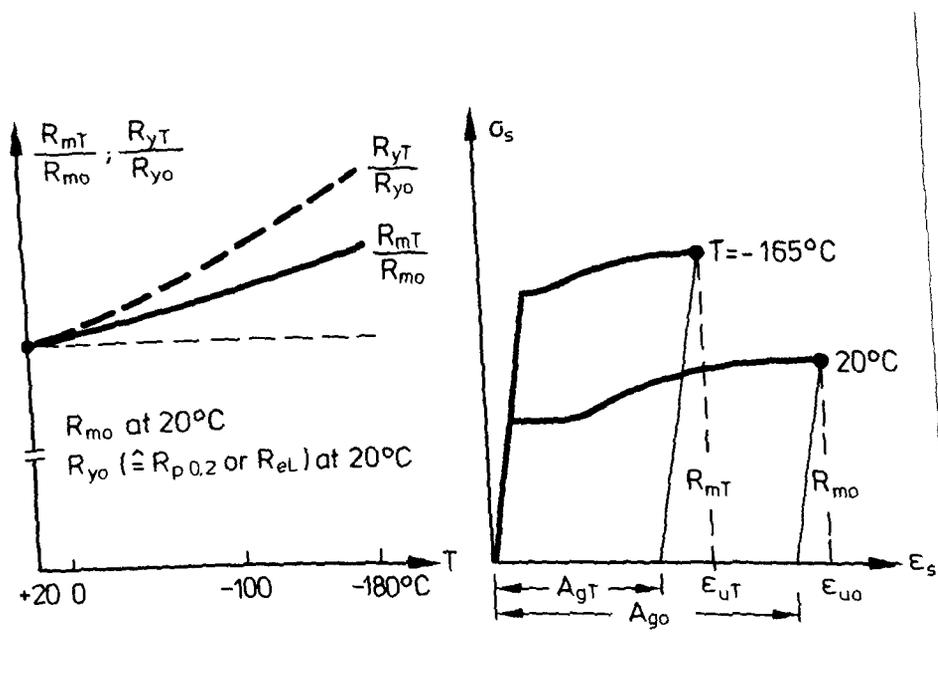


Fig. 6.5: Schematic stress-strain-lines for hotrolled deformed reinforcing steel, temperature-dependence of strength values

This fact is depicted in Fig. 6.6 for unnotched rebar in the as-fabricated state. This figure indicates several facts derived from experiments. While some rebars exhibit a very low transition temperature (temperature or temperature range connected with brittle, i.e. increasingly non-plastic failure), others do not, though belonging to the same strength class according to EU 80, but being fabricated in different plants or by different manufacturers /15, 18, 19/. Some Ni- or Cr-alloyed steels may maintain their ductility throughout the entire range of relevant cryogenic temperatures /20/.

The inherent ductility of a reinforcing steel must be available for the reinforcing work and for the load carrying capacity with a ductile mode of failure as well. The inherent plastic potential of the steel can be expressed by its uniform plastic strain A_g at break. Due to cold bending and rebending of the bar with the diameter d_s over a pin roller with the diameter D_b , a portion of the plastic potential is consumed:

$$\Delta A_{gb} \approx \frac{d_s}{D_b}$$

Certainly, this loss of ductility occurs only in the edge fibres of bar. Welding also entails a loss of ductility.

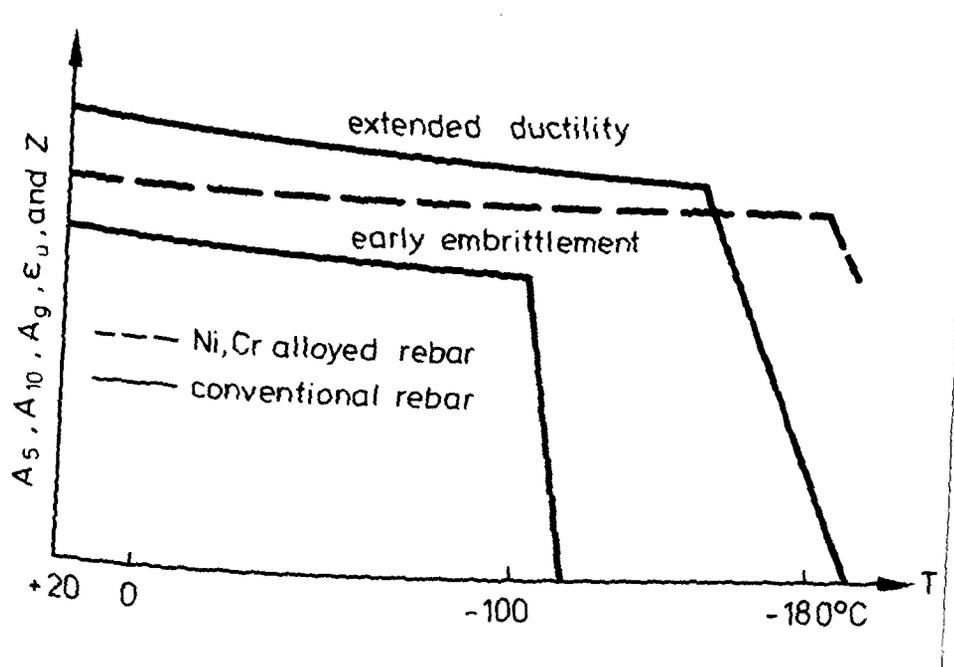


Fig. 6.6: Mechanical ductility values of reinforcing bars vs. temperature

In the limit state design according to the CEB-FIP-Model Code /21/, Fig. 6.7, the total steel strain at failure should not exceed 1%. One of the reasons for the restriction of the total steel strain is that a certain ductility reserve should be kept available for unaccounted stresses and for plastic redistribution of moments. This reserve is denominated by A_{gres} .

The loss of ductility in course of bending of a bar ranges between 5 and 7% for bends with roller diameters of 15 to 20 d_s (though it is bad detailing practice to place bends in regions of high steel stress). There are only few data available on the uniform plastic elongation A_g of reinforcing bars. Mostly, the values of A_{10} and A_5 are measured, following standards requirements. Conventional rebars, suitable for arc welding, of the strength classes 420/500 and 500/550 and of high ductility show values of $A_g \geq 8$ to 12% at normal temperature. Thus, the ductility reserve beyond the total plastic strain of CEB-FIP can be estimated to range between 3 and 5%. The ductility requirement is then expressed in terms of the total strain at failure of the bar by:

$$nec \ \epsilon_{Tu} = \frac{R_{yT}}{E_{sT}} + 3\%$$

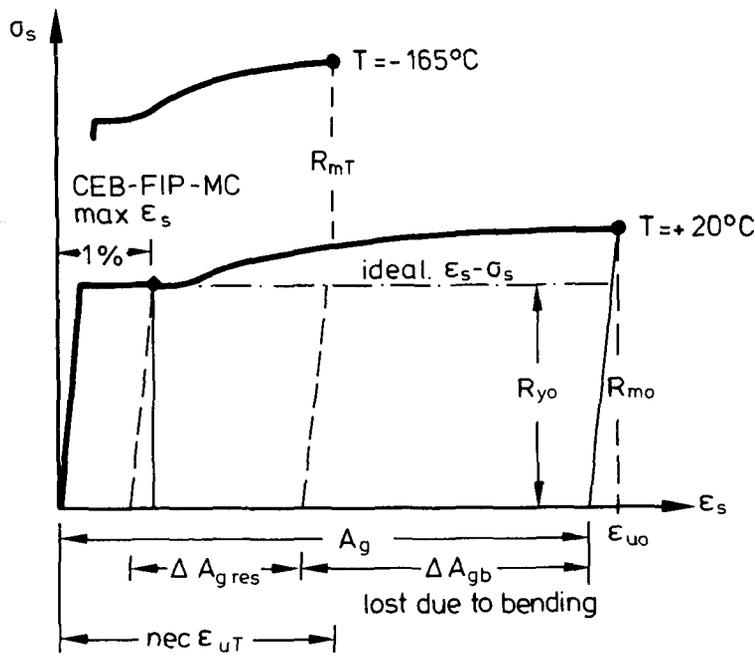


Fig. 6.7: Stress-strain lines of reinforcing bars and ductility requirement

This value shall be exceeded by each test value of sec. 5.2.4.3.

This ductility requirement has several limitations. It is only valid for static load conditions. If the hazard scenario includes dynamic forces acting on members in the cryogenic state, also the influence of elevated strain rates must be dealt with (example: the p/c-inner tank under seismic action). If the hazard scenario includes the liquid impulse loading of the outer tank, the dynamic strength of steel, still being at + 20 °C, must be known. The ductility criterion is only valid for straight bars, the effects of welds and mechanical couplers are unknown.

6.3.3 Notch sensitivity

Even at room temperature the presence of notches will, because plastic stress reduction is prevented by the multiaxial stress conditions at the base of the notch, increase the tendency for the steel to undergo brittle fracture, and this tendency is further increased by low temperatures.

On account of their surface roughness and more particularly also on account of their ribs reinforcing steel bars are to be regarded as "systematically notched bars". This notch effect is taken into account in the tensile tests with bars in

the as-fabricated state. Other unintentional notches may occur in consequence of local damage during work on the site. It is therefore necessary to consider how and by what surface damage to the steel the toughness behaviour is affected. In /1/ an overview of the parameters causing notch action and embrittlement is presented.

Embrittlement due to a notch depends upon, among other conditions, the notch shape coefficient α_k which represents the ratio of the maximum longitudinal stress at the base of the notch to the nominal stress (A_{sk} -cross-section of the notched bar):

$$\alpha_k = \frac{\max \sigma}{\sigma_n} \geq 1; \quad \sigma_n = \frac{F}{A_{sk}}$$

The notch shape coefficient is, for ideally brittle-elastic materials, a function of the notch geometry (Fig. 6.8); α_k increases with increasing notch depth and notch sharpness ρ . In the notch test the "notched tensile strength"

$$R_{mk} = \frac{F_{uk}}{A_{sk}}$$

is compared with the tensile strength of the unnotched specimen

$$R_m = \frac{F_u}{A_s}$$

For a brittle material the so-called notch-sensitivity ratio is defined as follows:

$$N_{sr} = \frac{R_{mk}}{R_m} = \frac{1}{\alpha_k} \leq 1$$

On the other hand, if $R_{mk}/R_m \geq 1$, it means that ductile fracture behaviour exists, the ductile behaviour being the more pronounced as the ratio

$$\frac{R_{mk}}{R_m} \geq 1$$

exceeds the value of 1.

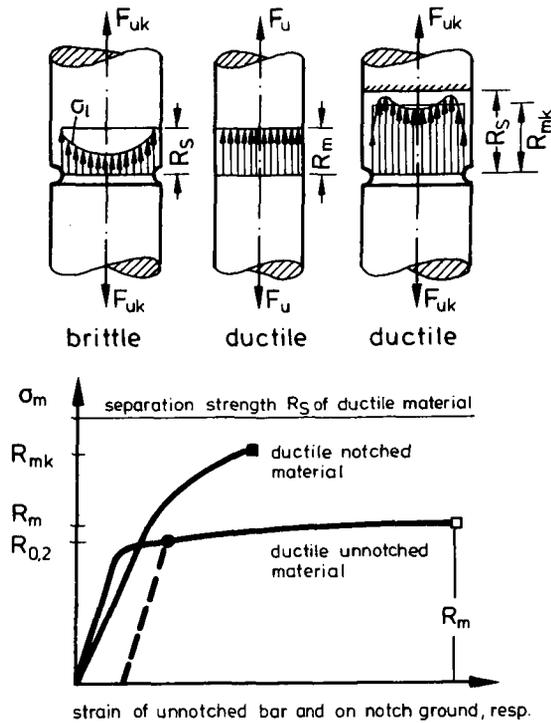


Fig. 6.8: Notch action for a ductile steel

Fig. 6.9 shows schematically the dependence of the notch sensitivity ratio of reinforcing bars as a function of temperature. One type of bar exhibits an early embrittlement, the other remains ductile for $T > - 160 \text{ }^\circ\text{C}$. Behaviour is influenced by the parameters of composition, fabrication, and also by the notch geometry [1]. The ductility requirement of sec. 6.3.1 implicitly states that the cold yield strength R_{yT} of the unnotched reinforcing steel shall be transgressed. Thus, the following strength and ductility requirement for bars with notches according to Fig. 5.1 can be formulated:

$$\frac{F_{ukT}}{F_{yT}} \geq 1$$

F_{ukT} ultimate force of notched bar at low temperature T

and

F_{yT} yield force of unnotched bar at low temperature T

$$\text{nec } \epsilon_{ukT} \geq \frac{R_{yT}}{E_{sT}} + 1 \%$$

ϵ_{ukT} ultimate strain of notched bar on free length outside notched section

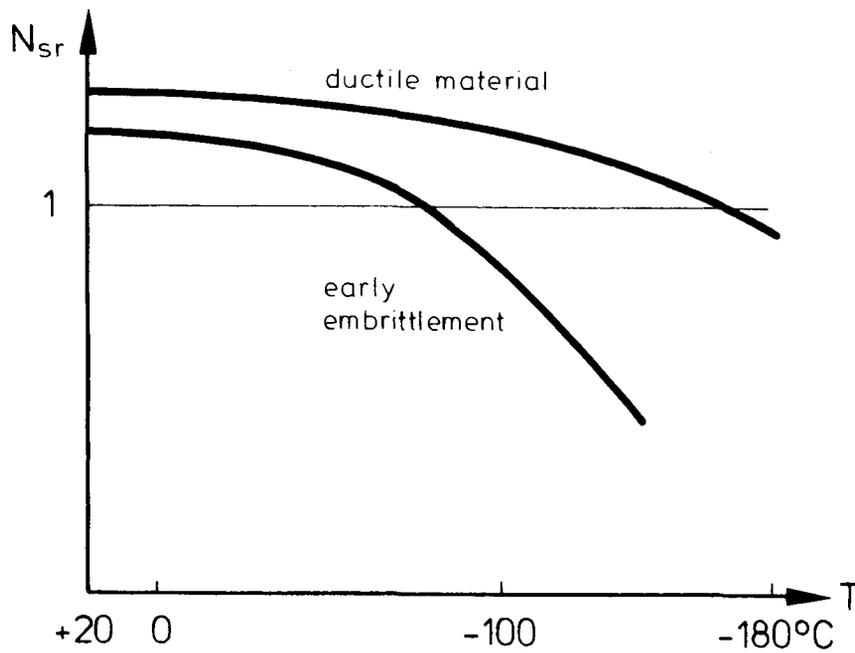


Fig. 6.9: Notch sensitivity of reinforcing bars as a function of temperature for a certain type of notch

These requirements serve for the selection of steel material of low susceptibility to accidental surface injury occurring in course of transport and construction works. The effect of such surface injuries on the load carrying capacity of structural members is nil. The probability that such a flaw on a bar is located in a structural crack and that it simultaneously coincides with a point of high steel stress is extremely low.

6.3.4 Necessary strength class for crack control

In the case of a local or even global thermal shock, acting on the inner surface of the outer tank, thermal eigenstresses and restraint actions will be generated. As a consequence cracks will arise. For the reason of tightness of the outer tank the width of such cracks must be controlled by reinforcement stressed within its elastic range of steel stress (also for the sake of limiting the tensile strains of the welded steel liner).

Tests and calculations show that a thermal shock will LNG causes a temperature of about - 120 °C to - 140 °C in the plane of the inner reinforcement. This temperature causes a resultant thermal strain of about

$$\text{res } \epsilon_T \approx \alpha_T (-120 \div -140 - 20) \approx -1.5 \text{ ‰},$$

which is also the strain that leads to restraint; it also corresponds to the mean steel strain measured over cracks

$$\epsilon_{sm} \approx -\text{res } \epsilon_T$$

Because of bond transfer and of concrete's participation in carrying tensile forces between cracks, the steel strain ϵ_{scr} in a primary crack exceeds the mean strain ϵ_{sm} :

$$\epsilon_{scr} > \epsilon_{sm}$$

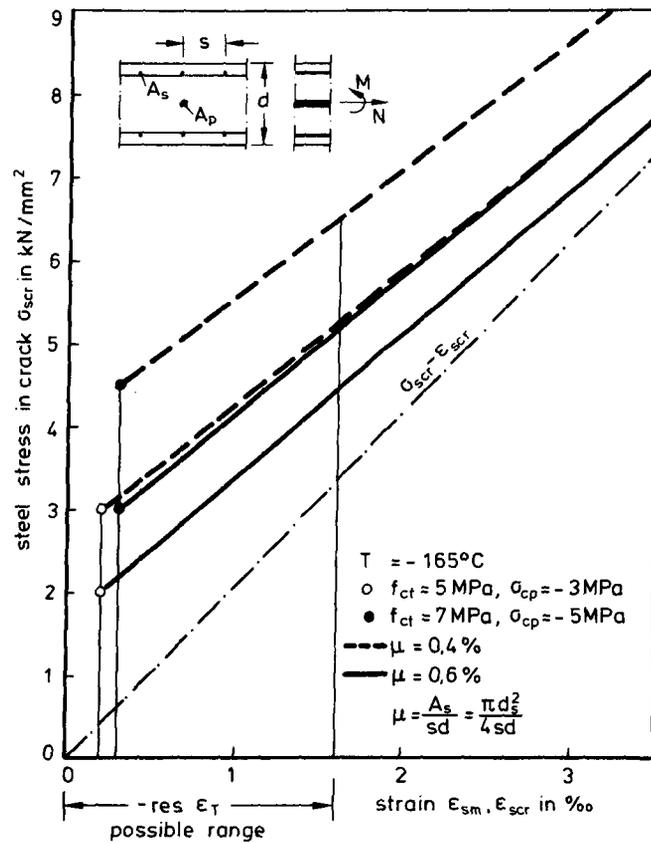


Fig. 6.10: Steel stress in crack in a section subjected to restraint actions vs mean steel strain (example)

A set of internal actions M and N due to restraint, which transforms the section into the cracked state, leads to the steel stress σ_{scr} in the cracked section. The dependence of the steel stress on the mean strain is shown in Fig. 6.10. It is a function of the tensile strength of concrete, of the reinforcement ratio μ , of the concrete stress σ_{cp} due to axial prestress, etc. Though, the lines of Fig. 6.10 depend on many parameters, the practical range is well covered. It can be deduced, that for reasonable values of the reinforcement ratio the steel stress due to restraint will not exceed 600 MPa. Thus, there is really no need for high-strength reinforcement. Bars of the strength class 500/550 are sufficient, considering the increase of yield strength due to low temperature. Crack control and other actions may even lead to a higher reinforcement ratio. Then, a higher strength class may become necessary.

6.4 Requirements for prestressing steel

The vital role of the prestressing tendons on the structural integrity and tightness of a RLG tank is well known. Many of the remarks on reinforcing steel in sec. 6.3 apply to prestressing steel as well.

There is no need to investigate the sensitivity of a prestressing steel to notches on the free length of a tendon. The worst situation with respect to notch action a prestressing steel is subjected to, occurs in the tendon-anchorage assembly. Thus notch sensitivity is verified in the test of the tendon-anchorage assembly. The avoidance of notches on the prestressing steel's surface during the insertion of the tendon into the duct by careful operation is good standard practice.

Tests on tendon-anchorage assemblies proved that a satisfactory mechanical efficiency can only then be attained if a prestressing steel with a high ductility at room and cryogenic temperature as well is chosen (also other factors are important). From all ductility values which are can be measured in a tensile test, the constriction Z proved to be the most suitable information to disclose the prestressing steel's susceptibility to brittle failure. This important information cannot reliably be derived from the ultimate plastic strains A_5 , A_{10} or A_g . As shown by Fig. 6.11 the constriction Z shows a steep drop at the temperature T_M , marking the transition from ductile to brittle failure [23]. The measurement of constriction should be accompanied by inspection of the fracture surface by means of light-microscopy and SEM.

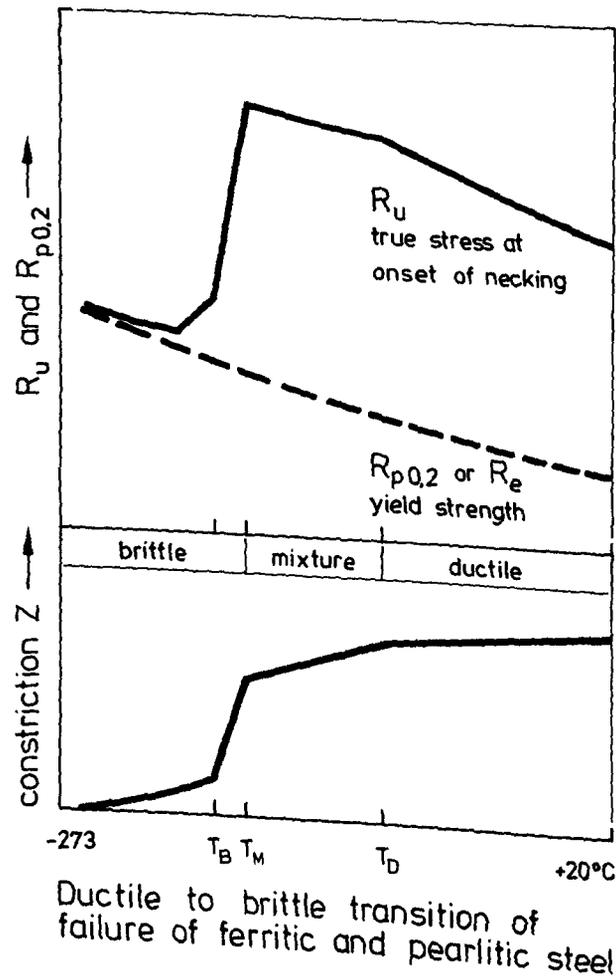


Fig. 6.11: Ductile to brittle transition of failure of ferritic and pearlitic steel

Tests have proven that cold-drawn and stabilized wires and seven wire strands, if of the low relaxation type, will exhibit a high anchorage efficiency at cryogenic temperature if the transition temperature T_M is below the boiling temperature of the stored gas (e.g. $T_{LG} \approx -165^\circ\text{C}$ for LNG):

$$T_M \leq T_{LG} - 10^\circ\text{C}$$

The Figs. 6.12 and 6.13 show typical test results which fulfill this requirement. Not enough data are available for hotrolled, cold-drawn and stress-relieved bars and for quenched and tempered wire. For cold-drawn, stress-relieved wire and for stabilized strand the following ductility requirements should be met in order to fulfill the requirements of sec. 6.5.1:

$$\text{meas } Z(-165^\circ\text{C}) \geq Z_M(T_M) \geq 30\%$$

with

$$T_M \geq T_{LG} - 10^\circ\text{C}$$

and

$$\text{meas } Z(-165^\circ\text{C}) \geq Z(20^\circ\text{C}) - 10\%$$

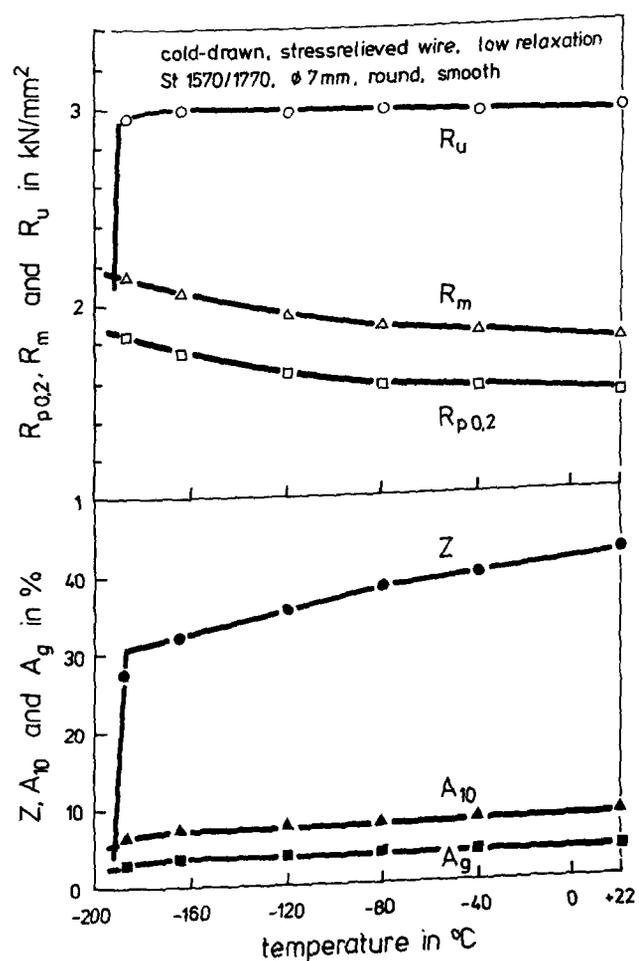


Fig. 6.12: Mechanical properties of cold-drawn and stress-relieved wire vs. low temperature

Furthermore:

$$\text{nec } \epsilon_{uT} = \frac{R_{yT}}{E_{pT}} + 3 [\%] \quad \text{at } T = -165 \text{ } ^\circ\text{C}$$

Because of lack of test data it is not possible to formulate requirements for quenched and tempered steel or hot rolled, cold-drawn and relieved bars.

6.5 Requirements for prestressing systems

6.5.1 Requirements for the tendon-anchorage assembly

The requirements for satisfactory behaviour for normal temperature application are formulated in the FIP-Recommendations /11/, which are in accordance with most national requirements (Fig. 4.18). They state in essence (for mode b, testing of prototypes).

- The actual strength of the prestressing steel must not be significantly reduced by anchorage effects. This demand is verified by the measured anchorage efficiency:

$$\text{meas } \eta_A = \frac{F_{tu}}{\min F_{cu}} \geq 0.97, T = 20 \text{ } ^\circ\text{C}$$

- The ductility of the prestressing steel, expressed as total strain on the free length of tendon at failure, must not be significantly reduced by anchorage effects. This is verified by

$$\text{meas } \epsilon_u \geq 2.3 \% \quad T = 20 \text{ } ^\circ\text{C}$$

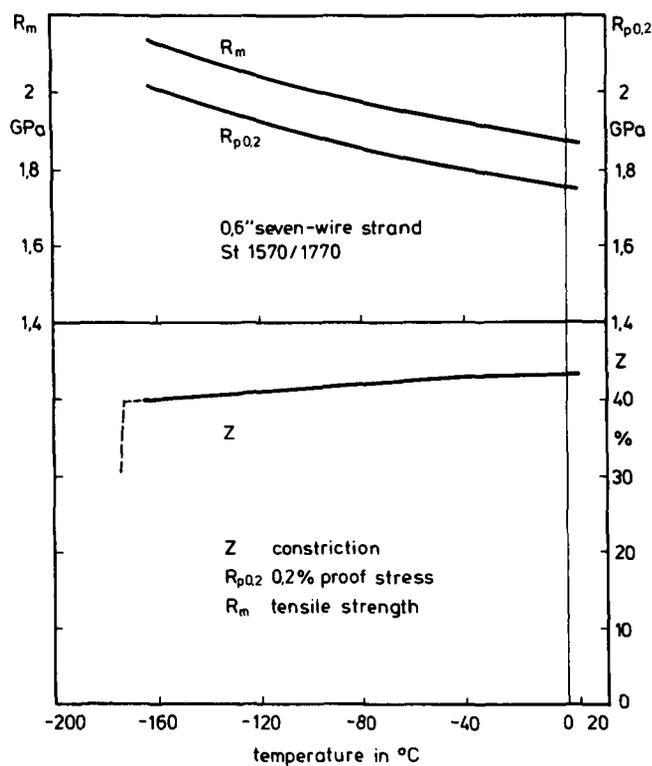


Fig. 6.13: Mechanical properties of stabilized seven wire strand vs. low temperature

The requirements for low temperature application may also be based on these demands /17/ (Fig. 6.14). But, since the limit state design will not make use of the increase in strength due to low temperature, emphasis is to be put upon the ductility demand: brittle failure of the tendon-anchorage assembly must be precluded. This leads to the following requirements for a satisfactory cryogenic behaviour:

- The strength of the tendon-anchorage assembly must exceed the cold yield-strength of the cable (n units). This is verified by:

$$\frac{F_{tuT}}{F_{cyT}} \geq 1 \quad \text{at } T = -165 \text{ } ^\circ\text{C}$$

F_{tuT} breaking strength of tendon-anchorage assembly at $-165 \text{ } ^\circ\text{C}$

F_{cyT} nominal mean cold yield strength of cable of n units at $-165 \text{ } ^\circ\text{C}$

The total strain at failure must at least be equal to the total permissible steel strain of the limit state according to the CEB-FIP-Model code plus an additive plastic strain increment $\Delta\epsilon = 1 \%$ to account for redistribution etc.:

$$\text{meas } \epsilon_u \geq \epsilon_{p0} + 2\% = \text{tot } \epsilon_{pu} \text{ (CEB-FIP)} + 1\% \quad T = -165 \text{ } ^\circ\text{C}$$

with ϵ_{p0} being the steel strain due to post-tensioning:

$$\text{meas } \epsilon_{uT} \geq \epsilon_{pymT}$$

The mechanical properties of the prestressing steel, both at normal and low temperature, must be determined by at least 10 single unit tests. At least three tests of the tendon-anchorage assembly, at $+20 \text{ } ^\circ\text{C}$ and $-165 \text{ } ^\circ\text{C}$, are necessary. It is advisable, to perform also tests on single-unit tendon-anchorage specimens to verify the strain requirements if the strain measurement on the complete tendon becomes impossible. Test methods are dealt with in sec. 4.6.3 and 5.4.2.

6.5.2 Requirements for the anchorage zone

Test methods etc. are dealt with in sec. 4.6.4 and 5.4.2. The requirements of /11/ for normal temperature have also to be met.

The metallic anchorage components and the reinforcement within the anchorage zone shall not fail prematurely. This is ensured if the failure load of the load transfer test exceeds the nominal cold tensile strength of the cable $F_{Au} \geq n A_{pm} f_{ptm} (-165^\circ\text{C})$.

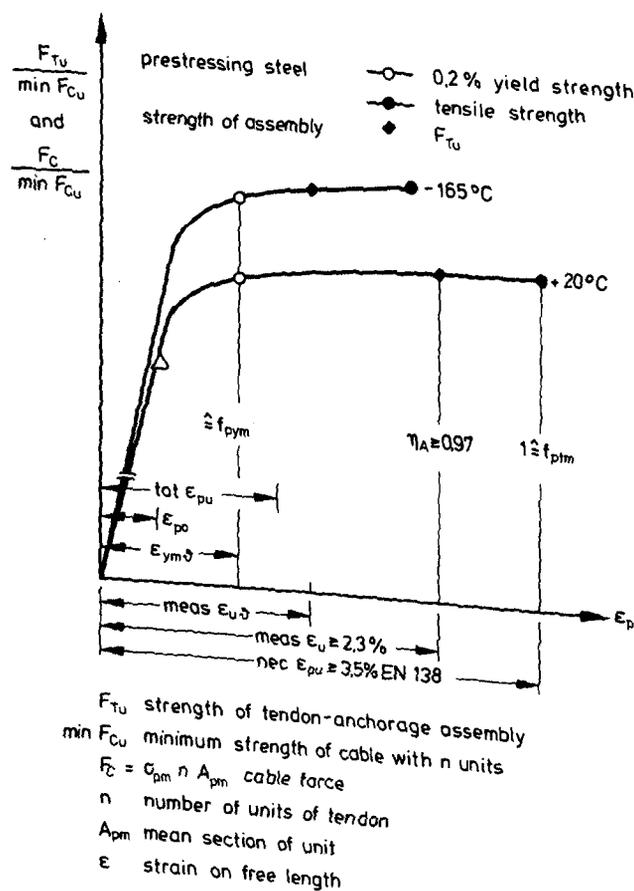


Fig. 6.14: Requirements for tendon-anchorage assembly for normal and cryogenic temperature

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