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Behaviour at cryogenic temperatures of tendon anchorages for prestressing concrete

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Tendon anchorages are sensitive zones where fractures may be produced and this risk may be increased at low temperatures. No international standards for tendon anchorages at low temperatures have yet been developed. This paper aims at two objectives: to furnish information on the behaviour, at low temperatures, of two commercial tendon anchorage systems and to make some proposals, as well as related testing procedures, for pre-stressing systems intended for cryogenic applications.

1. INTRODUCTION

There is a growing interest in pre-stressed concrete structures working at low temperatures. To date, the principal application of pre-stressed concrete at cryogenic temperatures has been for the storage of liquified gases or as a secondary structure to prevent spillage from primary containers. Other applications at low temperatures devised in the Arctic include: mobile exploratory drilling vessels for oil exploration and production; tankers for transport of oil and liquified natural gas (LNG); floating terminals and industrial plants. This interest was reflected in two international conferences on Cryogenic Concrete [1, 2] held in 1981 and 1982, and a symposium on Concrete Sea Structures in Arctic Regions in 1984 [3].

Tendon anchorages are sensitive zones where fractures may be produced and this risk may be increased at low temperatures. For cryogenic applications it is important to note that, whether or not the cold strength of the pre-stressing tendon is utilized in structural analysis, the tendon anchorage assembly does not fail in a brittle fashion. For low temperatures, no international rules (as to the testing procedure and the necessary ductility requirements for the tendon anchorage system) have yet been developed. This paper has two purposes: to furnish information on the behaviour at low temperatures of two commercial tendon anchorage systems and to suggest some requirements, as well as related testing procedures, for pre-stressing systems intended for cryogenic applications.

2. BASIS FOR AN EXPERIMENTAL METHODOLOGY

2.1 Background

Tendon anchorage systems may fail due to breaking of the wedges, failure of the tendon far from the anchorage or inside the anchorage. Anchorage failures are classified as ductile or brittle. Ductile failures may be avoided in the knowledge of the yield strength of the material. To avoid brittle fracture, it is necessary to know the fracture toughness [4] at the relevant temperature and the size of the maximum expected crack. In general, machined parts have defects less than 0.1 mm (0.004 in.), but moulded parts may have small voids, or inclusions, that act as stress raisers, like small cracks. In such cases it would be worthwhile to establish control procedures for anchorage parts in order to guarantee no defects higher than some specified size.

Tendon failures are also classified as ductile or brittle. In practice, ductile failure is guaranteed when certain values of stress or strain from a tensile tests are above minimum figures specified in some requirements. Brittle fracture, at low temperatures, is related to the fracture toughness of the tendon [5] and the critical size of the defect. Initial defects triggering brittle fracture in tendons are rare, nevertheless such defects may grow in a stable way by fatigue or stress-corrosion and produce delayed brittle fractures.

Tendon failures inside, or near to, the anchorages are more frequent and difficult to characterize by means of simple tests on anchorage or tendon materials alone. Sometimes, failures are due to wire rupture at wedge indentations and slippage of the central wire. In practice, the behaviour of the tendon anchorage system has to be characterized empirically by direct tensile tests of the assembly [6]. At low temperatures, the strength of the tendon and anchorage components is usually greater than at ambient temperature and no problems should arise regarding strength. Ductility, on the other hand, tends to decrease and minimum values at low temperatures should be established. An added difficulty, regarding the characterization of the tendon anchorage assembly, is that the mechanical response is also influenced by the rate of loading, as will be shown later.

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2.2 Experimental programme

To check all the above-mentioned modes of failure a minimum experimental programme should include:

1. Tensile tests on the steel in the anchorage, as well as the measurement of fracture toughness at the relevant low temperatures;
2. Tensile tests on steel tendons;
3. Tensile tests on tendon anchorage assembly at low temperature and with a loading schedule dependent upon the expected operating conditions and hazards.

Tensile tests 1. and 2. should not pose problems regarding standardization, if standards for room temperature are followed. If ductility is measured as uniform elongation, the size of the sample will not be relevant. Testing temperatures have to be specified as well as the accuracy and temperature profile along the sample. When testing anchorage materials, the sample orientation should be identified. The influence of rate of loading is checked in this paper and the relevance of accuracy and uniformity of the temperature profile along the sample has been discussed elsewhere [7].

The measurement of fracture toughness for anchorage materials is standardized [4]. This value is necessary for designing anchorages against brittle fracture in the presence of small defects.

Tests on tendon anchorage assembly are less well defined. In cases where this assembly may be subjected to low temperature, its static strength must be known and investigated. At present, no international rules for such test method have been established. Thus, the FIP Recommendations [8] may serve as a guideline. To take into account that prestressing is usually done at room temperature, tendons were stressed first, then cooled and finally stressed until rupture. Some other tests, at low temperatures, have been done in this research programme and described subsequently. The aim of these tests is to clarify whether the low temperature, in conjunction with the load cycles, leads to an embrittlement of the assembly.

The experimental programme includes the following tests at liquified natural gas temperature, −165°C (−265°F):

Steel used for anchorage; tensile tests at two straining rates, 10^{-5} s^{-1} and 10^{-3} s^{-1}. Fracture toughness tests [4].

Steel tendons; tensile tests at two straining rates, 10^{-5} s^{-1} and 10^{-3} s^{-1}.

Tendon anchorage assembly; static tensile tests, after preloading at room temperature, according to the schedule sketched in Fig. 1(a). Cyclic tests have been scheduled as for high risk structures, following ACI standard for concrete reactor vessels and containments [9]. Low-cycle high-amplitude tests, 50 cycles between 0.8 F_m and 0.4 F_m, where F_m is the maximum load at room temperature. Testing schedule is sketched in Fig. 1(b). High-cycle low-amplitude tests, according to Fig. 1(c). 500.000 cycles between 0.66 F_m and 0.60 F_m, plus 300 cycles between 0.7 F_m and 0.6 F_m. Thermal cycling tests, two cycles, according to the schedule depicted in Fig. 1(d), to check the effect of thermal coupling between dissimilar steels.

3. MATERIALS AND TEST PROCEDURES

3.1 Characterization of materials

Two pre-stressing systems have been studied according to the experimental programme previously described.

In System 1, tendons are made of 15.24 mm (0.6 in.) strands of 7 wires, individually anchored by wedges. Cold-drawn stabilized wires are used in the strand manufacture. Anchorages were made with non-alloyed carbon steel. The mechanical properties of the wires and of the steel for the anchorages at room temperature are summarized in Table 1.

In System 2, tendons are made of straight 7 mm wires anchored by means of button heads. Cold-drawn, stabilized wires of eutectoid steel have been used. As in system 1, plain carbon steel was used for anchorages. The mechanical properties of the wire and steel for anchorages at room temperature are shown in Table 2.

The following specimens have been tested:

Tensile tests on steel for anchorages; cylindrical specimens, 7 mm diameter, with a free length of 130 mm and a gauge length of 50 mm.

Fracture toughness tests on steel for anchorages; compact tensile specimens (C.T.S.) according to ASTM E399 [4], 25 mm in thickness.

Tensile tests on steel for tendons; button headed wire specimens (central wire was used for strands), with a free length of 250 mm and a gauge length of 50 mm.

Tendon anchorage assembly tests; for both systems a single unit composed of a strand, or wire, with its corresponding anchors was used as specimen. Specimen length was 900 mm and gauge length was 500 mm for strands and 50 mm for wires.

3.2 Testing equipment

Tensile and toughness tests were performed in an Instron temperature cabinet modified to bring temperatures down to −170°C. Tests were performed at −165 ± 1°C with a maximum temperature difference along the specimen of 1°C, and the specimen centre slightly hotter than its ends, in accordance with the recommendations given in [7].

Tendon anchorage assembly tests were performed in a modular cryogenic chamber especially designed and constructed for this purpose. The chamber had three modules with independent temperature control in order to achieve a good uniformity in temperature. The maximum temperature differences along the specimen were less than 2°C.

Loading was performed by means of a servohydraulic testing machine. The loading up to the rupture phase was run in displacement–control mode and in load–control

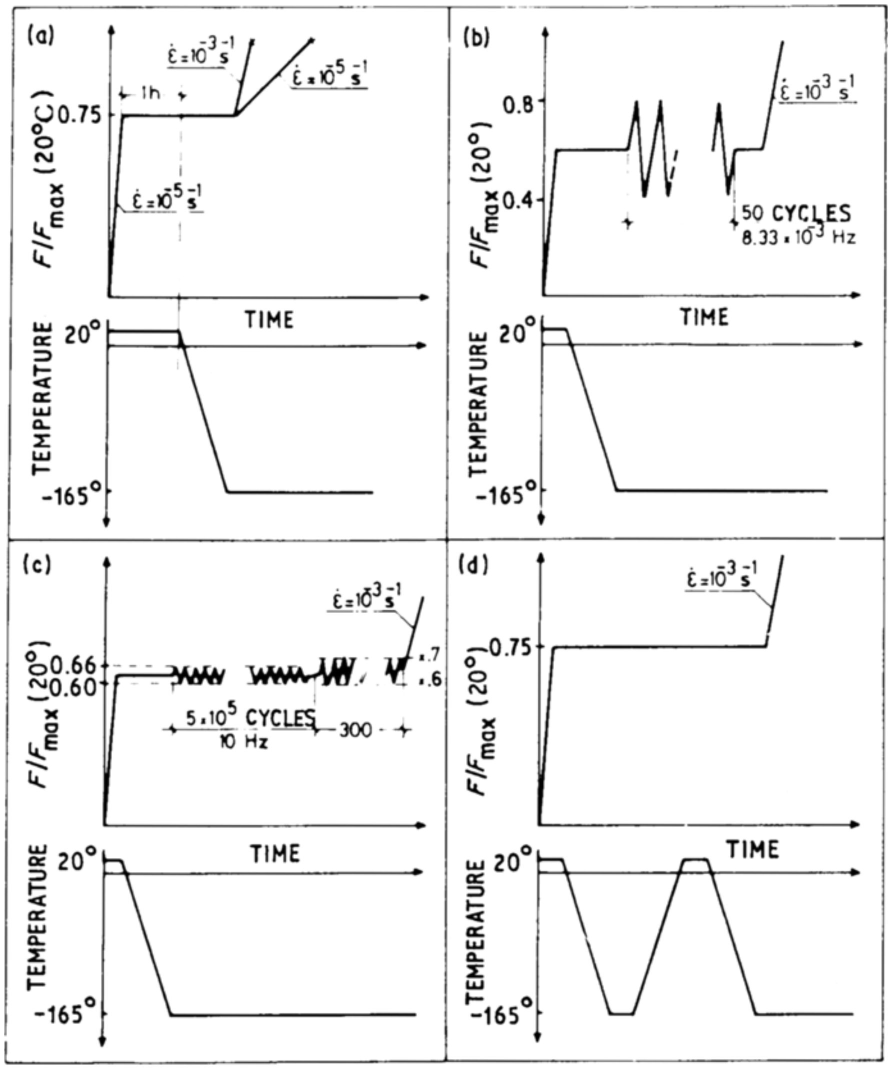


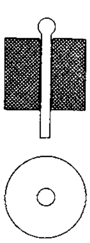
Fig. 1 Tests for tendon–anchorage assemblies; (a) 'Static' tensile; (b) Low cycle high amplitude; (c) High cycle low amplitude; (d) Thermal cycling.

Table 1 Mechanical properties at 20°C of steels from system 1

	Yield stress $\sigma_{y,0.2}$ (MPa)	Rupture stress σ_R (MPa)	Elongation under maximum load ϵ_M (%)*
Central wire	1620	1790	5.4
Anchorage	330	600	15.2

*See text for gauge length.

Table 2 Mechanical properties at 20°C of steels from system 2



	Yield stress $\sigma_{y0.2}$ (MPa)	Rupture stress σ_R (MPa)	Elongation under maximum load ϵ_M (%)*
Wire	1530	1740	5.4
Anchorage	500	670	7.4

*Gauge length, 50 mm.

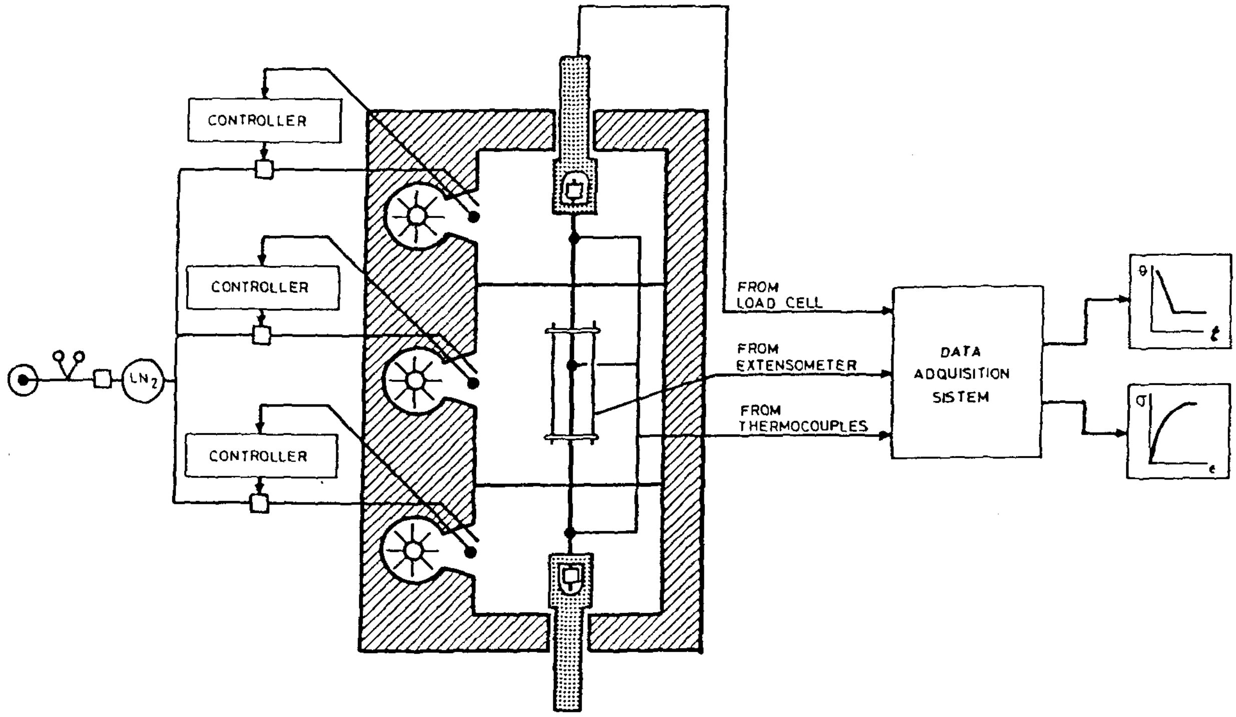


Fig. 2 Experimental set-up for testing tendon-anchorage assemblies at low temperatures.

mode during preloading or cyclic loading stages. The loading cell used provided an accuracy of 5% and a resolution of 50 N in load measurement.

Strain measurements on wires, over 50 mm gauge length, were performed with an MTS extensometer with 0.25% accuracy. Strain in strands, over 500 mm gauge length, was measured with a specially designed device using inductive displacement transducers as the sensory elements. The accuracy of the measurement was better than 1%.

Load and strain evolution was continuously recorded and simultaneous readings were taken by an automatic data acquisition system and stored in a digital tape for subsequent processing. Fig. 2 shows schematically the experimental set-up for testing tendon anchorage assemblies.

4. EXPERIMENTAL RESULTS

4.1 Anchorages

The main results of the tensile and fracture toughness tests, at −165°C, are summarized in Table 3. Each figure is an average from two tests.

Differences in strength for low and medium strain rates are small for system 1 steels, and undetectable for those of system 2. Ductilities, measured as elongation under maximum load, do not show any significant influence of the strain rate in the range under study.

Comparison with the room temperature properties (Tables 1 and 2) show that, on cooling down to −165°C, there is a noticeable increase in strength, while the uniform elongation slightly decreases for system 1 anchorage (20%) and increases for system 2 anchorage (35%).

4.2 Prestressing wires

Tensile tests results, at −165°C, for pre-stressing wires from both systems, are summarized in Table 4. Strain rate sensitivity is negligible with regard to strength and ductility.

The increase in strength, due to cooling, is about 15% relative to room temperature values, while uniform elongations are equal or slightly higher than those at room temperature. This behaviour almost coincides with reported figures for similar steels [6].

4.3 Tendon-anchorage assemblies

Tables 5 and 6 show the results of the five types of tests performed on tendon anchorage assemblies. The mean features of the observed behaviour are analysed subsequently:

4.3.1 *Influence of cyclic loading and cooling*

A glance at the results included in Tables 5 and 6 shows that the influence of the previous cyclic tests, mechanical or thermal, on the strength and ductility of the tendon anchorage assemblies are very small, as compared with the values for monotonic tests with the same strain rate to rupture (10^{-3} s^{-1}).

A more detailed assessment using the Student's test

Table 3 Mechanical and fracture properties, at −165°C, for anchorage materials

	Tensile properties Strain rate $\dot{\epsilon}$ (s^{-1})	Yield stress σ_y (MPa)	Rupture stress σ_R (MPa)	Elongation under maximum load ϵ_M (%)	Fracture toughness K_{IC} (MPa $m^{1/2}$)
Steel for anchorage 1	10^{-5}	730	830	12	39.0
	10^{-3}	750	850	12	
Steel for anchorage 2	10^{-5}	850	910	10	39.4
	10^{-3}	850	910	10	

Table 4 Mechanical properties, at −165°C, for wire materials

	Strain rate $\dot{\epsilon}$ (s^{-1})	Yield stress $\sigma_{y,0.2}$ (MPa)	Rupture stress σ_R (MPa)	Elongation under maximum load ϵ_M (%)
System 1 central wire	10^{-5}	1910	2090	5.4
	10^{-3}	1970	2100	4.9
System 2	10^{-5}	1780	2020	6.4
	10^{-3}	1790	2000	6.3

Table 5 Test results at −165°C for system 1

Type of test	σ_R (MPa)	ϵ_M (%)	Fracture location
Monotonic $\dot{\epsilon} = 10^{-5}\ s^{-1}$	2120	5.3	At anchor–tendon interface. Initiated at wedge indentation.
Monotonic $\dot{\epsilon} = 10^{-3}\ s^{-1}$	2090	5.5	Centre of tendon by necking
Low cycle	2110	5.2	Centre of tendon by necking
High cycle	2090	—	Centre of tendon by necking
Thermal cycling	2110	4.9	Centre of tendon by necking

Table 6 Test results at −165°C for system 2

Type of test	σ_R (MPa)	ϵ_M (%)	Fracture location
Monotonic $\dot{\epsilon} = 10^{-5}\ s^{-1}$	2020	4.5	Near button head by necking
Monotonic $\dot{\epsilon} = 10^{-3}\ s^{-1}$	1970	5.0	Centre of tendon by necking
Low cycle	1980	5.1	Centre of tendon by necking
High cycle	1980	5.2	Centre of tendon by necking
Thermal cycling	1990	5.3	Centre of tendon by necking

shows, indeed, that the differences in mean value, with reference to the monotonic 10^{-3} s^{-1} tests, are not significant for a 5% confidence interval.

4.3.2 *Influence of the strain rate*

The strength results for monotonic tests run at 10^{-3} and 10^{-5} s^{-1} shown in Tables 5 and 6 show a slight influence of the strain rate. A Student's test to a 2% confidence level showed that the differences were significant, although perhaps negligible for engineering design (less than 2% difference).

Nevertheless, it should be noted that lower strength corresponds to the higher strain rate. This effect is attributed to self heating of the tendon due to plastic work and, as it will be explained below, it is not an intrinsic property, but depends on the experimental set-up, especially on the convective heat transfer.

4.3.3 *Strength and ductility*

Leaving aside the slight influence of strain rate mentioned above, the strength values obtained in all tests correspond extremely well to those deduced from tests on single wires (Table 4).

Elongation under maximum load for tendon anchorage assemblies is also similar to those of wire specimens tested either at room or at low temperature. The minimum requirements proposed in [6] have been exceeded in all tendon anchorage assemblies tests. Moreover, the elongation under maximum load was always higher than 2.3%, the minimum value recommended by the FIP for prestressing systems at room temperature [8].

4.3.4 *Fracture patterns*

Tables 5 and 6 show a systematic difference in fracture pattern between tests run at different strain rates. In tests performed at 10^{-3} s^{-1} failure occurred through plastic instability and the fracture took place in the central portion of the tendon, with necking of the wires (Fig. 3).

For the lower strain rate tests (10^{-5} s^{-1}), system 1 specimens systematically failed at the anchorage–tendon interface, in a sequential manner (wire after wire). Fracture was always initiated at an indentation produced by the wedge and two different patterns were observed: shear fracture (Fig. 4) and transverse crack growth (Fig. 5). System 2 exhibits, in the tests, a systematic failure through necking localized near the button head.

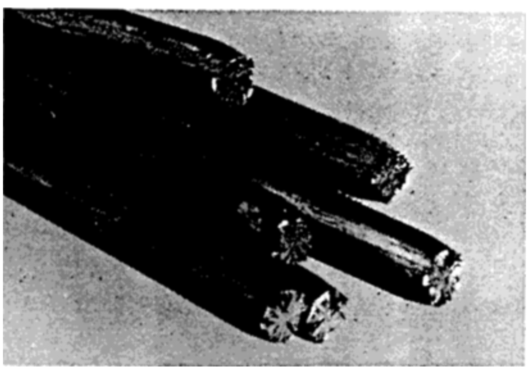


Fig. 3 Tests at $\dot{\epsilon} = 10^{-3}\,s^{-1}$. Fracture took place in the central portion of the tendon.

Fig. 4 Tests at $\dot{\epsilon} = 10^{-5}\,s^{-1}$. (System 1) Fracture initiated at an indentation produced by the wedge. Shear fracture.

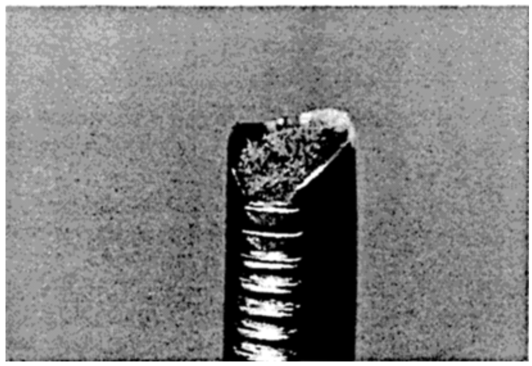


Fig. 5. Tests at $\dot{\epsilon} = 10^{-5}\,s^{-1}$. (System 1) Fracture initiated at an indentation produced by the wedge. Transverse crack growth.

As in the case of the influence of the strain rate on the strength, the difference of localization and pattern of fracture appearing at different strain rates is thought to be due to the self heating of the specimen, discussed below.

4.3.5 *Environmental effects*

Once it was suspected that the effects of the strain rate upon strength and failure type could be explained by a self-heating effect, some tests were performed with temperature recording during the loading up to fracture.

In the low-rate tests, temperature increase was negligible, while for the faster strain rate, a temperature increase of the central part of the specimen of about 15°C was measured.

Since the self-heating effect is due to the energy dissipation due to plastic work, the temperature increase will depend on the straining rate and on the convective effects. It will, then, depend upon the particular cooling chamber used in the experimental set-up.

Since the strength of the wire decreases when temperature increases, the self-heating can explain why the strain rate effects the failure stress, but in order to explain the abrupt change in fracture pattern, it is necessary to assume a non-uniform temperature increase along the specimen.

The following quantitative approach is founded on the following hypotheses:

H_1 The isothermal strength of the wires is negligibly affected by the strain rate in the range of non-dynamic loading ($\dot{\varepsilon} < 0.1\ s^{-1}$) at low temperatures;

H_2 The strength of the wires decreases with increasing temperature;

H_3 The anchors act as a heat sink in such a way that the temperature increase in the tendon–anchorage interface is negligibly small compared to the temperature increase in the central portion of the specimen.

Let T_N be the nominal temperature of testing, ΔT, the temperature increase in the central portion of the specimen. σ_{uw} (T_W) the ultimate tensile strength of the wire (tendon) at temperature T_W, σ_{ui} (T_i) the ultimate strength for failure, at the interface of the anchor and tendon and σ_u the ultimate strength of the assembly. Then clearly,

$$\sigma_u = \min\left[\sigma_{uw}(T_W), \sigma_{ui}(T_i)\right] \quad (1)$$

We also assume that for a strictly isothermal situation $T_w = T_i$, the failure always occurs at the tendon–anchorage interface due to the damage caused by the anchor to the wires, at a mean stress

$$\sigma_{ui}(T) = \eta\, \sigma_{uw}(T) \quad (2)$$

where $\eta \leq 1$. We write formally H_1 and H_2 in the form

$$\sigma_{uw}(T_N + \Delta T) = \sigma_{uw}(T_N)(1 - \alpha\,\Delta T) \quad (3)$$

for small ΔT of, let us say, approximately 15°C. H_3 simply states that

$$T_i = T_N \quad (4)$$

Substitution of Equations (2), (3) and (4) in (1) gives

$$\sigma_u = \min\left[\sigma_{uw}(T_N)(1 - \alpha\,\Delta T), \mu\,\sigma_{uw}(T_N)\right] \quad (5)$$

from which the following conditions derive:

If $\eta < (1 - \alpha\ \Delta T)$, the failure will take place at the tendon anchorage interface.

If $\eta > (1 - \alpha\,\Delta T)$, the failure will take place at the centre of the specimen due to plastic instability.

Since the temperature sensitivity coefficient α is about 10^{-3} $(°C)^{-1}$ for this type of steel [5], and the measured temperature increase is, as mentioned above, about 15°C, the fracture location change can happen if $\eta \geq 0.985$. By comparison of the relevant values of Tables 4, 5 and 6 it is obviously our case. It can be concluded that the self-heating, along with hypothesis H_1 to H_3, can explain the observed behaviour.

It follows from this simplified analysis that for high efficiency (η) systems, the failure mode can depend strongly on the experimental conditions, a fact to be taken into account in the test design and interpretation, as well as in the future recommendations for low-temperature testing of tendon-anchorage assemblies.

5. SUMMARY AND CONCLUSIONS

5.1 Anchorages

Ductile failure of anchorages at low temperatures will be avoided if such elements are designed to avoid plastic collapse at room temperature, due to the increase in strength as temperature decreases.

Design, to prevent brittle failure, should be based on fracture mechanics and the knowledge of the fracture toughness of the steel at the relevant working temperature.

5.2 Steel tendons

Tests performed on 7 mm diameter cold-drawn wires and central wires of a 15.24 mm (0.6 in.) 7 wire strand, exhibit an increase in strength of about 15% and values of elongation under maximum load similar to those at room temperature. These results are similar to other reported figures [6] and are adequate to establish full confidence in such steels, up to LNG temperatures. Loading rates from $10^{-3}\ s^{-1}$ to $10^{-5}\ s^{-1}$ scarcely influenced the results.

5.3 Tendon-anchorage assembly

At low temperatures, regardless of utilization of the cold strength of the pre-stressing steel in the structural analysis, the tendon anchorage assembly does not fail in a brittle fashion. This means that the failure load of the assembly, at the relevant temperature, should exceed the cold yield strength of the pre-stressing steel tendon or strand. This basic requirement may be complemented by imposing a minimum elongation, as has been done for room temperature recommendations [8]. Nevertheless, the reasons for such additional requirement are not clear [6] and if a figure is proposed when the structure is pre-stressed at ambient temperature, it should be less than the corresponding figure at a warm temperature, since elongation requirements are higher during the post-tensing operation.

The static strength of tested tendon–anchorage assemblies at low temperature can be classified as satisfactory. The failure loads are in excess of the cold yield strength of the pre-stressing steel and the elongation under maximum load much higher than the recommended at warm temperature (e.g. 2.3% in [8]). The speed of testing had little effect on maximum load and elongation, but influenced the rupture mode of the steel tendon. Slow tests ($\dot{\epsilon} = 10^{-5}\ s^{-1}$) produced failures inside the anchorage and intermediate tests ($\dot{\epsilon} = 10^{-3}\ s^{-1}$), failed far away from the anchorage. As explained above, this effect is thought to be due to local heating of the tendon. This should be borne in mind when designing experiments or assessing experimental results.

Dynamic and thermal cycling tests have been performed with no signs of distress. At the end of cycling the assemblies were stressed until failure. Rupture loads and elongation were similar to static tests.

In conclusion, this research has proved that ductility requirements for tendon–anchorage assemblies at cryogenic temperatures can be met, if the pre-stressing steel itself and the metallic anchorage components maintain sufficient ductility and toughness. While the notch sensitivity of button heads is virtually nil, wedge-type anchors function by creating surface notches on the pre-stressing steel. Thus, at low temperatures the design of the anchorage is even more decisive than at normal temperatures because of the increasing embrittlement due to notches. However, providing a choice of suitable materials and a sound design of the components involved are made, no problems will arise. Naturally, the suitability of a pre-stressing system developed for normal temperature application does not guarantee its suitability at low temperature; it has to be ascertained by testing at the relevant low temperatures along the lines suggested in this paper.

6. REFERENCES

1. 'Cryogenic Concrete', Proceedings of the 1st International Conference of the Concrete Society, Newcastle upon Tyne, March 1981 (Construction Press, 1982) pp. 336.
2. 'Cryogenic Concrete' Proceedings of the 2nd International Conference of the concrete societies of the Netherlands and UK. Amsterdam. (Devon House, London, October, 1983).
3. 'Concrete Sea Structures in Arctic Regions', Proceedings of Calgary Symposium, 1984, p. 109.
4. ASTM Standard E399. 'Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials.' Annual book of ASTM standards, Section 3. Vol. 03.01.
5. Elices, M. 'Fracture of Steels for Reinforcing and Prestressing Concrete' in *Fracture Mechanics of Concrete*, G.C. Sih and A. DiTommaso, Eds (Martinus Nijhoff Publishers, 1985) p. 276.
6. Elices, M., Rostasy, F.S., Faas, W.M. and Wiedemann, G. 'Cryogenic Behaviour of Materials for Prestressed Concrete'. (FIP State-of-the-Art Report, Wexham Spring, Slough, 1982) p. 84.
7. Planas, J., Corres, H., Elices, M., Sánchez-Gálvez, V. 'Tensile Tests of Steel at Low Temperatures. Problems due to Non-Uniformity in the Temperature Distribution along the Specimen', in Proceedings of the 2nd International Conference of the concrete societies of The Netherlands and UK, Amsterdam, October 1983.
8. FIP. 'Recommendations for Acceptance and Application of Post-Tensioning Systems.' FIP R.5.9, (March 1981) Wesham Springs, Slough, p. 30.
9. ACI Standard 359.74. 'Section III: Rules for Construction of Nuclear Power Plant Components. Division 2: Code for Concrete Reactor Vessels and Containments.' ACI-ASME.