Full-scale, Low-temperature Mechanical Testing of Prestressing Systems

by R. Christen, A. Bergamini and K. Ghazi Wakili

ABSTRACT—For a number of industrial applications, concrete prestressing elements are exposed to extremely low temperatures during their lifetime. This can cause concerns regarding their possible embrittlement. The investigation of the mechanical properties of individual materials of these systems at different temperatures is a routine task. Numerical methods are a reliable method for the calculation of stress and strain fields in complex geometry systems and load patterns, as long as a good knowledge of initial and boundary conditions is available. Temperature-dependent material properties can also be taken into consideration. The increased complexity of the calculations for a system under thermal and mechanical loads leads to a higher level of uncertainty in the results, as its cost in terms of required input and computing time increases. The obstacles in the way to a reliable numerical assessment of the safety of the operation of a prestressing system under extreme thermal conditions make the execution of full-scale system tests advantageous, in spite of the costs arising from the development of suitable technical means.

KEY WORDS—Low temperature, numerical methods, thermal analysis, structural testing, environmental effects

Introduction

Prestressed concrete is the solution of choice for the structural demands of many industrial and civil applications. In most cases, the execution of fatigue or static tensile tests at room temperature (i.e., temperatures varying between 20°C and 30°C) is considered as sufficient proof of the applicability of a prestressing system. To perform such tests, facilities with sufficient capacity, developing loads in excess of 15 MN, have been designed and built in several laboratories in Europe, Asia and North America, such as Laboratoire Central des Ponts et Chaussées (LCPC) in France,¹ TU München in Germany, and Construction Technology Laboratories (CTL) in the United States.²

In the case of some specific industrial applications, such as gas storage facilities at low temperatures or facilities located in areas with extreme climatic conditions, the embrittlement

behavior of the anchorage components at low temperatures can be of concern for the designers. The assessment of the behavior of individual materials with respect to their mode of failure by standardized methods, such as Charpy tests, is a routinely performed task both for industrial and research purposes.^{3,4} The behavior of individual strands under purely axial stress as well as the interaction between wedges and strands under the most diverse conditions has been widely investigated. The anchor plates have a complex geometry and are subject to complex stress fields. Numerical models make it possible to dimension complex bodies with a high level of confidence. Nevertheless, a full-scale test of the anchor plates is of major importance when designing a prestressing system,^{5–7} especially when they are subject to conditions close to worst case operational environment, such as unusually low temperatures.

Very limited information is available about the execution of full-scale mechanical tests on prestressing systems at low temperature.^{8,9} While in most cases the size of the tested sample does not represent an obstacle or a challenging development task, the development of the means and methods needed to perform a test of an unusually large prestressing cable at low temperature represents a technological challenge by itself.

In the case described in the present work, the worst-case scenario chosen for the test required one anchor plate of a 55 strand cable to be cooled to a temperature of -40°C . The goal of the development of a cooling system was to reach the desired temperature as quickly as possible in an economical and safe manner. Given the size of the system to be cooled (approximately 13 dm^3), a considerable time lag for the propagation of the temperature fronts was expected. A numerical model for the calculation of the volume temperature distribution, based on measurements performed on the surface of the sample, was needed to obtain a realistic estimate of the real test conditions.

Test Setup

Test Object and Requirements

The tested system consisted of a bundle of 55 strands, each 12.7 mm in diameter with a declared ultimate tensile strength of 10.1 MN. On both ends of the cable, identical anchorage systems were used. One of these was directly in contact with the testing machine and the other was supported by a reinforced concrete block. Since the main issue to be addressed by this test was the behavior of the anchor head under extreme thermal and mechanical conditions, the free length

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Original manuscript submitted: July 7, 2004.
Final manuscript received: November 9, 2004.
DOI: 10.1177/0014485105050908

TABLE 1—SUMMARY OF THE MECHANICAL PROPERTIES OF THE TEST SPECIMEN

Nominal diameter of one strand	12.7 mm
Nominal steel area of one strand	98.7 mm ²
Ultimate tensile stress	1860 N mm ⁻²
Minimum ultimate tensile strength of one strand	183.7 kN
Free cable length (approximately)	6000 mm
Number of strands	55
Nominal steel area of cable	5429 mm ²
Minimum ultimate tensile strength of cable (F_{pk})	10,103 kN
Anchor head diameter	320 mm
Anchor head thickness	160 mm
Concrete block dimensions	580×580×700 mm ³

of the cable and the uncooled anchor head were only used as auxiliary means for the execution of the test. In an actual structure, the free length of the cable would also be embedded in concrete. This part of the system is not considered critical, given the nature of the stresses in the strands. The most important properties of the test specimen are summarized in Table 1.

According to the application purpose, the test was carried out as follows. In a first step, the sample was loaded to approximately 73% of the declared tensile strength (F_{pk}) or 7375 kN. The load was then held constant while the cooling procedure started. This procedure was chosen because it is the closest possible to the extreme operational conditions that are expected to arise under exceptional circumstances, such as a liquefied gas leakage or similar. Given the complexity of the system, both from a geometrical point of view and because of the presence of various materials with different behaviors, a reality-like test was chosen. Once the required temperature ($T \leq -40^{\circ}\text{C}$) was attained, it was held approximately constant for 2 h, before the stress was increased at a rate of 100 MPa per minute up to 80% of F_{pk} or 8082 kN. Upon the customer's request, measures were taken to achieve a temperature distribution in the anchor head as homogeneous as possible (data not shown). Finally, the load was increased to the point of failure.

Mechanical Setup

The device used for the test was developed by Empa in the 1980s to perform static load tests on cables with forces up to 30 MN. At the core of the device, there is a pair of low friction hydraulic actuators, with 15 MN force capacity each. These actuators work on two crossheads, where the anchor blocks with several bearing plates are installed (Fig. 1). The nominal piston stroke of 120 mm is usually not sufficient to produce specimen failure under normal conditions. After the maximum displacement for each stroke is reached, the cable specimen must be unloaded to about 200 kN, so that a steel spacer plate can be inserted to compensate for any plastic deformation of the specimen. This procedure leads to the typical loading/unloading cycles in the load-displacement diagram shown in Fig. 6, where the plastic deformation between two cycles depends on the thickness of the inserted steel spacer plate. The test bed is designed to test cable systems of 5.5 m to 7.5 m length, while the maximum cable diameter is 250 mm.

Fig. 1—Photograph of the cooled side of the setup, partially insulated

Fig. 2—Diagram of the cooling/insulation system with sensor positions

Cooling System

The cooling system was specifically designed for the anchorage of the tested cable system. Effective homogeneous cooling, low cost and safe operation were the principal requirements on the system.

Due to its availability and low cost, liquid nitrogen (LN_2) was used as the cooling medium. It was circulated through a copper pipe, which was wound around the anchor block and thermally coupled to the system with heat transfer paste (Fig. 2). An additional winding on a copper plate was applied to the front face of the anchor head in order to increase the thermal contact surface.

In addition to the necessity to reach the desired temperature range within a reasonable time, safety considerations due to the potential of brittle failure of the system had to be taken in account. The nitrogen reservoir as well as the flow control valve was placed behind safety glass.

The efficiency of the cooling system was increased by insulating the cooled section from the environment and by means of a good coupling between the cooling medium and the specimen. As described in the previous section, a concrete block was introduced to simulate the interface between the prestressing system and the structure it would be installed in. The concrete block reduced the heat flow from the testing machine to the cooled anchorage. In addition, the whole anchorage was insulated with closed cell polymer foam plates from the environment (Jackodur CFX35-300 Standard). Additional protection from radiant heat was obtained by

wrapping the system in aluminum foil. For the cooling of the system to the desired temperature and subsequent execution of the final part of the tensile test, approximately 100 l of liquid nitrogen were needed over a period of 10 h.

Measurements

All measurements were recorded with a frequency of 1 Hz. Using pressure sensors integrated in the two hydraulic actuators, the force was calculated by means of the measured pressure and the active area of the hydraulic cylinder. The calibration of the force measurement showed a maximal relative inaccuracy of 0.5% within a range of 1–20 MN and fulfilled the class 1.¹⁰ The measurement of the total cable elongation fulfilled the class 1 as well and was realized by two incremental displacement sensors, which were measuring from a static reference point to the bearing plates on both sides. The sum of these two sensors gives the total elongation of the prestressing system.

In addition to the standard sensors for force and total displacement measurement, eight Pt100 temperature sensors were introduced to record the temperature at selected points (see Fig. 2). The temperature sensors T1, T4, T7, and T8 were applied along the copper pipe through which the cooling medium flowed. The remaining four sensors were placed directly on two strands, one on the cooled side and one on the room-temperature side of the cable. The distance between the cooled side (T2 and T5) and the room-temperature side (T3 and T6) was approximately 4 m.

Numerical Calculations and Validation

The numerical simulation of the transient (time-dependent) temperature distribution was carried out using VOLTRA,¹¹ a thermal analysis program for transient heat transfer in three-dimensional rectangular objects using the energy balance technique and respecting the guidelines of the European and International Standard EN ISO 10211-1.¹² The geometric model used as an input (Fig. 3(a)) represents only 1/8 of the whole assembly. This is admissible due to three planes of symmetry, which in turn were modeled by adiabatic boundary conditions (no heat fluxes perpendicular to these surfaces). By doing so, the complexity of the input data and the calculation time needed could be reduced remarkably. Another simplification concerned the modeling of the cooling unit by means of a convective boundary condition set at the top surface of the anchorage (Fig. 3(b)). As several sensors were placed along the copper pipe, the average value of these measured temperatures was set as a boundary condition temperature with an estimated value for the heat transfer coefficient $h_{cooling}$ of $400 \text{ W m}^{-2} \text{ K}$. This estimation is based on the thermal conductivity of the heat transfer compound and its approximate thickness of 0.5 mm representing a small resistance to the heat flux. The influence of the heat protective insulation layer around the anchorage was taken into account by a reduced value of the surface heat transfer coefficient to $3 \text{ W m}^{-2} \text{ K}$.

The material properties used in the model for transient calculations, i.e., thermal conductivity, specific heat capacity, and density are summarized in Table 2.¹³ The simulation was carried out for a grid with 64,500 nodes during a time period of 9 h 50 min at a time-step of 2 min.

Fig. 3—Input model for the transient calculation: (a) the geometric model including the planes of symmetry and the evaluated nodes N1, N2, N3, and N4; (b) the boundary conditions

Results and Discussion

The temperature distribution on the surface of the anchor head as well as force and displacement on the prestressing system were continuously measured during the temperature-controlled phase of the test.

The measured and the calculated temperature evolutions are shown in Fig. 4. For simplicity and clarity, only the average values of equivalent temperatures are presented. The maximum difference between these so-called equivalent temperatures is 7.4°C (between T1, T4, and T7) and 2.2°C (between T2, T5, and T8). The discontinuities in the curve of Avg T1 T4 T7 are due to manual adjustments of the liquid nitrogen flow in order to attempt to adjust the cooling rate. The average Avg T1 T4 T7 has been used as an input for the cooling boundary condition $T_{cooling}$. The comparison of measured average Avg T2 T5 T8 and the calculated average Avg N1 N2 N3 shows a very good agreement between measurement and calculation. The temperature at node N4 is colder due to its shorter distance to the cooling boundary condition. Based on these findings, the calculated temperature distribution at the anchor head (see Fig. 5) can be regarded as reliable, i.e., the temperature of the whole anchor head is below -40°C . As it was not possible to repeat the test without the insulation system to quantify its effectiveness, this was done by numerical simulations. For this purpose, a steady-state calculation with a fixed cooling rate of 6 kW m^{-2} applied to the front face of the anchor head was run twice: once in the original configuration, i.e., with the insulation material as shown in Fig. 2, and once with all the insulation material removed and replaced by air. A third run was carried out with the insulation removed but with a fixed cooling rate of 7 kW m^{-2} . The calculated temperatures at the nodes N1, N2, and N3 (see Fig. 3(a)) for all three runs are summarized in Table 3. These results show that an increase of at least 15% of the cooling power will be needed if the insulation is removed.

Figure 6 shows the load-displacement curve recorded during the test. The shaded background highlights the portion of

TABLE 2—SUMMARY OF THE THERMAL PROPERTIES OF MATERIALS FOR THE TRANSIENT CALCULATION

Material	Density (kg m^{-3})	Thermal Conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	Specific Heat Capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
Steel	7800	50	470
Air layer	0.2	1.0	1000
Copper	8300	300	385
Concrete	2700	2.4	800

TABLE 3—COMPARISON OF CALCULATED TEMPERATURES FOR THE SYSTEM WITH AND WITHOUT INSULATION

Calculated Temperature at	Steady State With Insulation and 6 kW m^{-2} Cooling Rate	Steady State Without Insulation and 6 kW m^{-2} Cooling Rate	Steady State Without Insulation and 7 kW m^{-2} Cooling Rate
Node 1	-77.0	-62.1	-75.8
Node 2	-76.9	-62.0	-75.7
Node 3	-75.3	-61.2	-74.7

Fig. 4—Measured (T1-T8; see Fig. 2) and calculated (N1-N4; see Fig. 3a) temperature evolutions. For simplicity and clarity, only the averages of equivalent temperatures have been represented

Fig. 6—Measured load-displacement curve. The shaded background highlights the portion that was performed at controlled temperature condition $< -40^\circ\text{C}$

Fig. 5—Calculated temperature distribution around the anchorage after 9 h 50 min. The distance between two consecutive isotherms is 5 K. Only the range between -40°C and -70°C is represented

the test that was performed at controlled temperature conditions. The behavior of the system immediately before failure confirms that no brittle failure took place. The majority of the wire failures in the system were located in the “warm” side of the cable. This is compatible with the observation⁴ made for various steel types, that the ultimate strength of steel increases with decreasing temperatures.

Only the portion of the temperature versus time curves utilized for the numerical calculations (600 min) is shown in Fig. 4. The actual duration of the test was 754 min. During the last 154 min, the liquid nitrogen flow was often modified in order to achieve a minimal temperature difference between measurement points.

Conclusions and Outlook

The experiment presented in this paper shows that adequate design of a cooling system allows the execution of a

full-scale tensile test on a prestressing system at low temperatures, in spite of the difficulties due to the large mass of the tested object. The experimental effort was completed by numerical calculations to validate the results of the experiment as a proof of concept for the use of a prestressing system under extreme temperature conditions.

The numerical calculation validated by comparing calculated and measured temperatures at accessible positions is able to predict/confirm the temperature values at some important but inaccessible positions within the test specimen.

The results of the test confirm available data about the safety of prestressing system at moderately low temperatures, as far as the anchorage area is concerned.

Furthermore, it can be shown that by optimizing the insulation and cooling system, lower temperatures and more homogeneous temperature distributions can be achieved. The comparably long duration of such test and thermal inertia of the system will allow performing in-line temperature distribution calculation as a support for control of the cooling system as well as for the determination of the point in time at which desired thermal boundary conditions are achieved.

In summary, we have described a complete approach to the execution of controlled temperature tensile tests on very large test specimens, spanning from a compact, low-cost cooling system to a method to interpolate temperature values for an inaccessible position within the specimen.

Acknowledgment

The authors wish to thank VSL Systems International, Subingen, Switzerland for their kind support and cooperation in the execution of the tests. Also, the authors would like to thank the technical staff of their respective laboratories for their precious support that made it possible to carry out the project.

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