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CFRP Tendon Prestress Monitoring by Resistance Measurement in a Spun Concrete Powerline Pylon

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ABSTRACT: More sustainable precast concrete elements are emerging utilizing high-performance spun concrete reinforced with high-strength, lightweight, and non-corroding prestressed Carbon Fibre Reinforced Polymer (CFRP) reinforcement. One example of this is a new type of precast CFRP pretensioned spun concrete pylon intended as powerline mast. One fundamental durability aspect that had to be assessed for validating this novel technique is the monitoring of the CFRP tendon prestress during service life of the thin-walled structural element. In this paper a monitoring principle for the tendon prestress based on the electrical resistance measurement of the unidirectional CFRP tendons is presented. The working principle of the direct resistance measurement was proven with a laboratory load test on a beam pretensioned by four embedded CFRP tendons. The implementation of this method in 2001 for the field monitoring of a full scale CFRP prestressed 27 m high powerline pylon has proven its reliability: The strain evolution of the prestressing CFRP tendons was monitored for several years and showed the expected low prestress losses.

1 INTRODUCTION AND MATERIALS: WHY USE CFRP PRESTRESSED HIGH PERFORMANCE CONCRETE ELEMENTS FOR CIVIL STRUCTURES?

Why should the new combination of materials 'CFRP prestressed high performance concrete' be beneficial for the prefabrication of structural concrete elements? The following discussion will deal with slender beams which are primarily subjected to bending and are manufactured in an adapted pre-tensioning method. In this context it should be noted that an eminent reference by Burgoyne (1997) discussing the fundamental issue of making rational use of advanced composite reinforcements in concrete comes to the conclusion that to be economic, advanced composites will be used for prestressing tendons (pre-tensioning resin matrix bar or wire systems are a viable option), but not primarily for passive reinforcement.

The CFRP prestressing reinforcement used in this work consists of fine, unidirectional carbon fiber-reinforced polymer tendons with a typical diameter of 5 mm, and is typically produced using the pultrusion method with an epoxy resin matrix. Unidirectional reinforced CFRP tendons have high design tensile strengths in the region of 2'000 - 2'500 MPa (Terrasi, 1998). The density of CFRP is 1.6 kg/m^3 which is barely one fifth of the density of prestressing steel. The tendons are coated with quartz sand in order to control bond to the high performance concrete (HPC). Perhaps the greatest advantage of CFRP as a prestressing reinforcement is its total immunity to corrosion in practically all relevant media, even if subjected to high mechanical stresses. The complete absence of any tendon stress-corrosion allows the concrete cover to be reduced to well below that necessary for the protection of prestressing steel tendons: the new Swiss civil engineering standard SIA 262 (2003) requires tendon covers between 45-65 mm depending on the environmental exposure class defined when designing the structure. Hence the 5 mm diameter CFRP prestressing tendons used in the first high-voltage transmission pylons manufactured by SACAC Schleuderbetonwerk AG in 2000 have a concrete cover of just 18 mm (Terrasi, 2001). The concrete cover size is determined on the basis of statical considerations (reception of the compressive stresses due to bending and of the bursting tensile stresses in the anchorage zone of prestressing reinforcements) and of the mismatch in thermal expansion coefficient between CFRP (transverse to fiber direction) and high-performance concrete (Terrasi, 1998). The extremely favorable CFRP fatigue properties and the absence of time-dependent mechanical prestress losses (creep and relaxation) should not be underestimated (Uomoto, 2001). On top of the high tensile strengths, the last mentioned properties in particular lend this material outstanding properties for the prestressing of concrete elements.

It should be mentioned as well that the modest mechanical properties of unidirectional CFRP tendons transverse to the fiber direction (in the range of 1%-5% of the corresponding longitudinal properties) must also be given careful consideration (e.g. in view of the anchorage of the prestressing tendons). Apart from this, the coefficient of thermal expansion (CTE) of the tendon transverse to the fiber direction is 2-3 times as high as that of HPC.

The high quality and the cost of sand-coated CFRP tendons, which is still elevated today with specific prices around 0.05 €/(m . kN) tensile capacity, require the same high quality for the concrete matrix: HPC with a strength class in the range of C90 to C100 is the appropriate partner material for the CFRP prestressing reinforcement. Typically, a very precisely batched fine-grain concrete (grain sizes from 0 to 8 mm) is used with high strength aggregates. The cement content is around 500 kg/m^3, micro silica and high-performance plasticizer are essential components of the recipes for these concretes, which have a water/cement factor of 0.30-0.35 for optimum workability. C90 to C100 high performance concretes are relatively inexpensive (with material costs of ca. 125 €/m^3) and have high durability, high bending-tensile strength (with 5%-fractiles over 5 MPa), a relatively high modulus of elasticity around 40 GPa (depending on the aggregates) as well as the high compressive cube strength of over 90 MPa. All these properties have a beneficial effect on the planned product.

The compaction of HPC can be achieved by centrifugal casting, vibration or -following a more advanced concrete mix design- by the self compaction. The treatment after casting often corresponds to a simple covering of the moulds in order to keep the young HPC humid for typically 36 hours before prestress release and demoulding.

From the advantages of the individual components CFRP and HPC mentioned above, it is possible to minimize the weight of the planned prestressed bending element by reducing the wall thickness while guaranteeing excellent service characteristics (no susceptibility to corrosion, high bending stiffness and high fatigue strength (Agyei, 2003). The outstanding durability of HPC prestressed with pultruded CFRP tendons has been confirmed by several field tests, in particular by the results of long-term (four-point bending creep) outdoor tests on three scaled spun HPC pylon sections subjected to extremely high bending loads which have been running at Empa for the last 14 years (Terrasi, 1998). The direct monitoring of the durability of the CFRP prestress needs more sophisticated measurement techniques, one possibility therefore is discussed in the following.

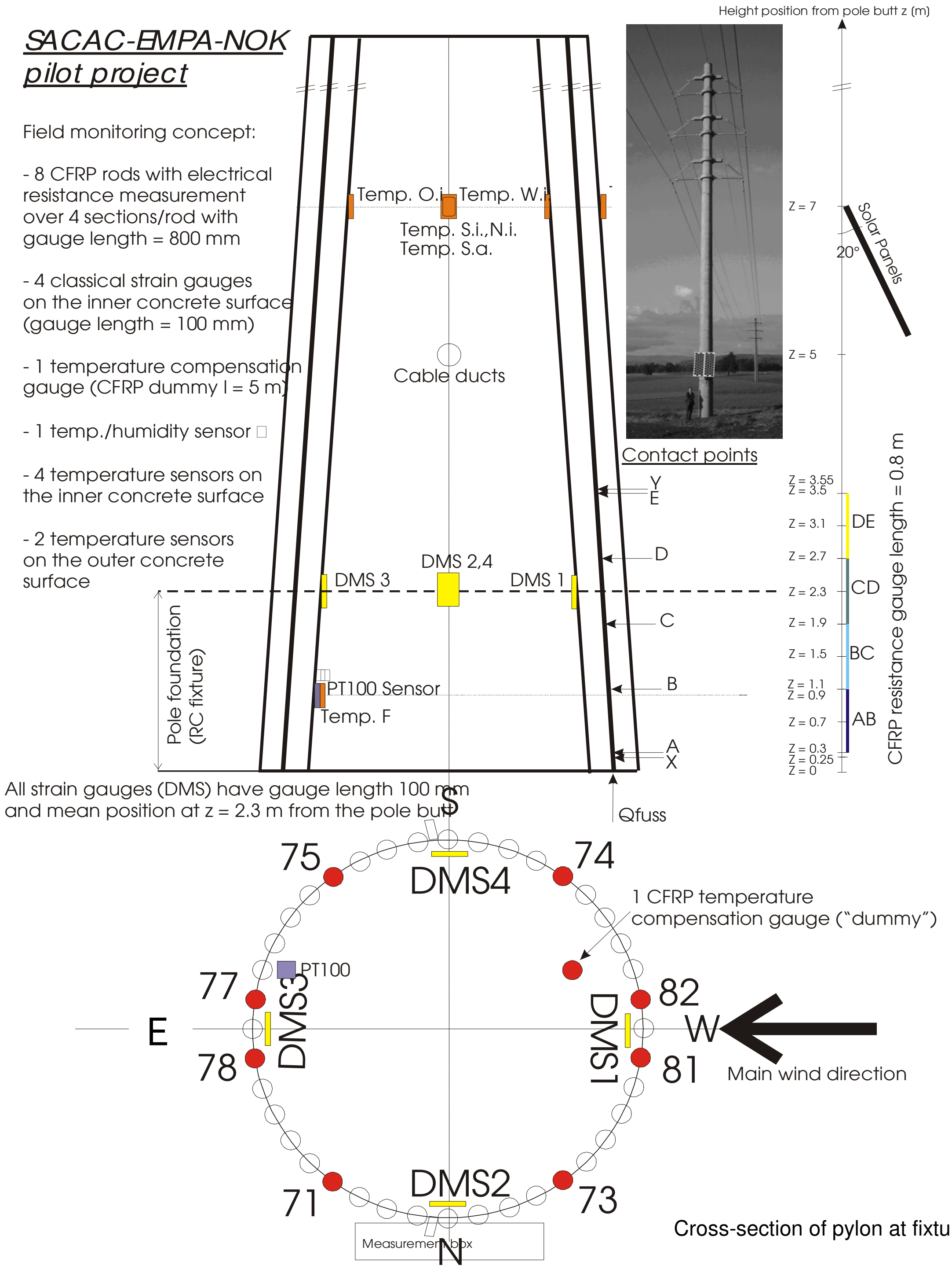

Figure 1. Sketch of pylon assembly with locations of sensing elements: The 8 monitored CFRP tendons (rods) are denominated with numbers 71, 73, 74, 75, 77, 78, 81, 82. Top right: monitored pylon in service.

2 PILOT PROJECT 'CFRP PRESTRESSED ELECTRICITY PYLON'

In 1994, Empa, the Swiss Federal Laboratories for Materials Science and Technology, embarked on a R&D project with the industrial concrete element prefabrication company SACAC AG. The aim of this project was to investigate the structural principles of passive (non-stressed) and active (prestressed) CFRP reinforcement of HPC for the production of tubular bending elements (pylons) (Terrasi, 1998).

A first full-scale field project was started in the year 2000: The Nordostschweizerische Kraftwerke (NOK, Power Companies of North-Eastern Switzerland) decided to install a pylon of this type for the first time in one overhead electricity power line of their 110 kV distribution network (Terrasi, 2001). A 27 m high pylon was produced for this project using an adapted pre-tensioning-spinning process (Terrasi, 1998). The conical pylon (see Figure 1) had an external diameter of 847 mm at the bottom and 529 mm at the tip (1.175% taper) with an average wall thickness of just 48 mm and a standard deviation of 4 mm. The minimum required design wall thickness was 40 mm. The C100 HPC cover on the CFRP tendons was only 18 mm. The concrete cover and the wall thickness were controlled using a geo-radar measurement system with a 1.5 GHz antenna as decribed by Hugenschmidt (2000) over the entire length of the pylon. The pylon weighed just 6'000 kg. This corresponds to a reduction in weight of 40% in comparison to a traditional steel-reinforced concrete pylon for the same application. A centric overall initial prestressing of 1'000 kN was produced via 40 fine CFRP prestressing tendons of 5.0 mm diameter (after prestress losses: σ_{pi} = 1'100 MPa, σ_{ci} = 7.5 MPa at the foot - σ_{ci} = 13.8 MPa at the tip of the pylon). This corresponds to an average prestressing reinforcement ratio of 1%. A rolltruded CFRP tape spiral (0.5-1 mm thick, 13 mm wide) was wound around the prestressing tendons served as the shear reinforcement.

The full-scale 27 m long pylon was subjected to cantilever bending tests at the Empa Structural Engineering Research Laboratory before field installation and fulfilled the requirements of the relevant regulation (Swiss regulation LeV, 1994) in terms of serviceability: The top deflection under maximum service moment 394 kNm (corresponding to a point load at the pylon's tip of 16 kN) was limited to 1.6 % of the cantilever length 24.6 m, 5% of the cantilever length are allowed by the relevant Swiss regulation LeV (1994). A maximum fixture testing moment of 492 kNm could be resisted with the opening of 88 fine bending cracks (of width < 0.3 mm) with an average spacing of 130 mm over a length of 11.5 m from fixture, in which the bending rotation was concentrated. After unloading a small residual deflection of the pylon of 50 mm could be measured. In the summer of 2001, NOK therefore installed the tested pylon in the Aargau canton (at Würenlingen) in their 110 kV overhead electricity power line 'Beznau-Baden' (Figure 1).

3 MONITORING

3.1 Strain on CFRP tendons

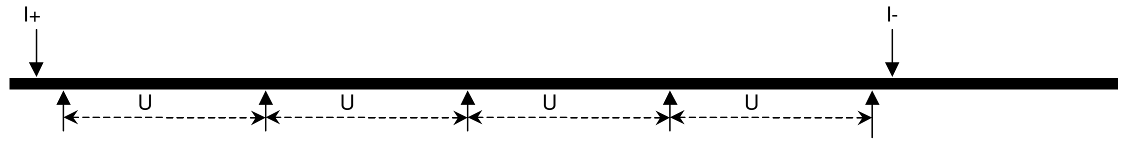

Figure 2. Principle for the strain measurement on CFRP tendons.

The detection of a possible bond creep in the anchorage zone of the CFRP prestressing tendons of the pylon is an essential forewarning information. Therefore, the strain of the prestressed

CFRP tendons had to be monitored in the area of the pylon's fixture. It is difficult to equip the tendon with strain sensors (gauges) in this particular environment without disturbing their bond to the concrete. However, carbon fibers show a dependence of their electrical resistivity on the strain comparable to an ordinary metal. This effect can be used to monitor the strain. Figure 2 shows the measurement principle. A current is guided through the tendons with the contacts at the position I+ and I-. Several electrical connections allow the measurement of the voltage drop along the tendon. The system is equivalent to a four wire resistivity measurement. Low resistance values and high temperature dependence of the resistivity are main obstacles. The resistance per section is around 0.8Ω. The monitoring system is solar powered and therefore only an excitation current of 100 mA was used resulting in a voltage drop of only 80mV. A strain of 1 µm/m corresponds to a voltage change of about 0.2 µV. To improve resolution and also to compensate thermoelectrical voltages, the current was reversed continuously and long integration times were used and a high stability current source was constructed with a short time stability of a few ppm. Also the temperature has strong influence on the measurement. The temperature coefficient of resistivity is around -430ppm/K corresponding to an apparent strain of ca. -200µm/m/K. To compensate temperature effects a dummy tendon was installed inside the pylon (Figure 1). Another challenge was to assemble the tendons in a way the contacts could survive the harsh production process (centrifugal casting of the concrete) and that the contacts were not sheared off in operation.

3.2 Monitoring System

The pylon is monitored remotely since its installation in 2001. A block diagram of the system is shown in Figure 3. It is an autonomous system built around a low power single board computer (SBC) running Linux.

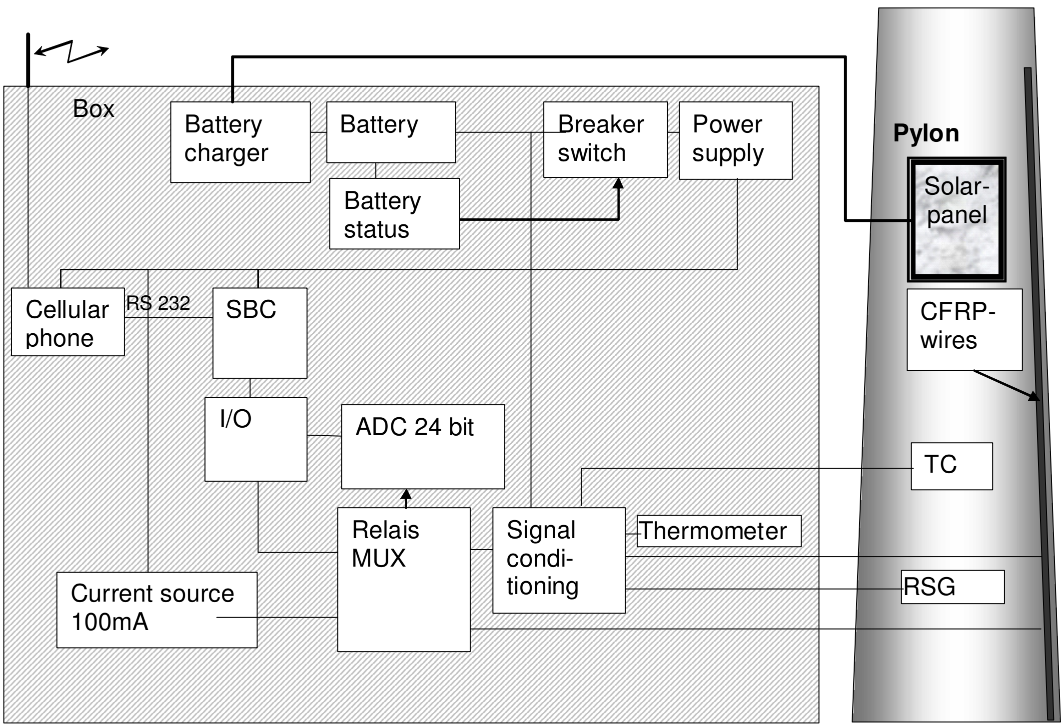

Figure 3. Block diagram of the monitoring system. Symbols: TC = Thermocouple, RSG = Resistance Strain Gauge, SBC = Single Board Computer.

The sensing system comprises eight monitored CFRP tendons each with four measurement sections, nine temperature, one humidity, four conventional resistance strain gauges and means to check the battery voltage and the solar panel current. The main components for the measurement system are a 24 bit ADC (analog to digital converter), a precision current source and some sixty bistable, dual contact, low thermal voltage relays. The relays connect the various sources to the ADC and also the current source to one of the monitored CFRP tendons. Measurements are performed at regular intervals and the results are stored. Via a cellular phone, it is possible not only to download the stored data, but also to completely control the Linux system via remote login. The system can also be programmed to send status reports and alerts by SMS either automatically or as a response. The complete system consumes less than 10 W and runs on a battery charged by a solar panel.

4 RESULTS

The working principle of the direct resistance measurement was proven with a load test on a beam prestressed by four embedded CFRP tendons. Figure 4 shows the four point bending test setup. The 2’300 mm long beam has a cross section of depth 160 mm and thickness 40 mm. The CFRP tendons are spaced by 40 mm and indicated as gray lines. Three of the tendons (denominated as wires A,B and C in Figure 4) have been connected with double contacts on both end faces for a four wire resistance measurement. The beam has then been loaded until failure. The results of the resistance measurement are shown in Figure 5. The markers indicate the measured temperature compensated resistance change. The resistance change is proportional to the load up 15 kN when cracks start to appear. The slope is proportional to the distance to the neutral line of the beam. The strong dashed lines indicate the expected resistance change derived from the elastic behavior of the beam and the measured strain vs. resistance relation of the CFRP tendons (in a laboratory tensile test, repeated for different temperatures and humidity conditions). Measurement and prediction show a good agreement in the linear region. As soon as cracks open, strong deviations and a shift of the neutral line are observable.

Each of the monitored CFRP tendons of the pylon (Figure 1) has four monitored sections of 0.8 m indicated as sections AB and BC in the foundation, CD in the fixture zone and DE in the free span above ground. In Figure 6 the measurement results of several tendons in the section CD are given. The main problem here is to make adequate temperature compensation because the compensation tendon is located inside the pylon hanging in the in air and not being integrated in the wall, therefore having different temperatures. To alleviate the situation only measurements taken around four o’clock in the morning are shown when the temperature distribution is expected to be homogeneous. Considering seasonal changes, a decrease of the tendon’s prestress of about 500 µm/m over five years can be observed.

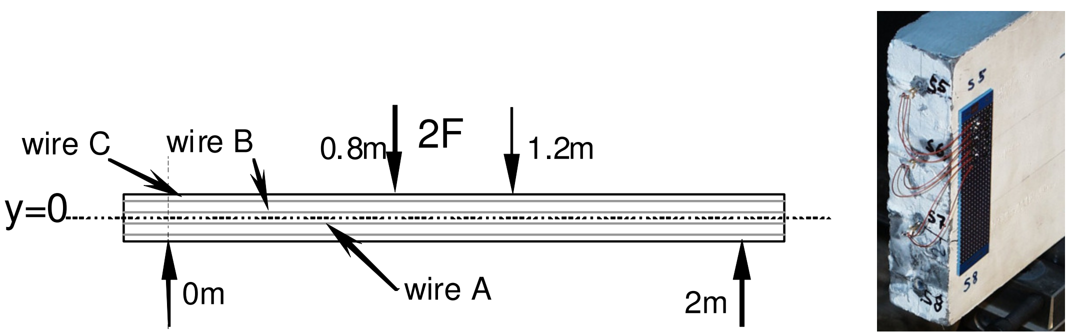

Figure 4. Four point bending test of a high strength concrete beam with embedded pretensioning CFRP tendons. The wiring for the resistance measurement is shown on the left.

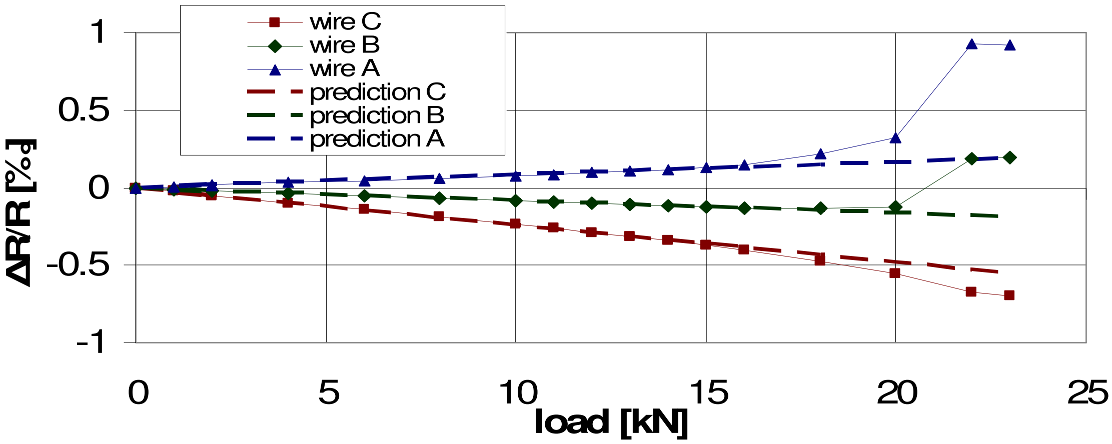

Figure 5. Comparison of measured and calculated resistance change during four point bending of a test beam according to Figure 4.

This corresponds to 7% of the initial prestress of the tendons (7200 µm/m) and is in good agreement with the estimate of the prestress loss due to creep and shrinkage of the HPC over five years from the start of the long-term field monitoring in April 2002 (450 µm/m).

In Figure 7 the relative resistance change of the lowest section of the dummy tendon is shown as a function of the temperature measured at the bottom inside the pylon. Data of the whole observation period are included. A linear dependence is clearly recognisable. Its fit yields a value of -423ppm/K. This agrees well with the laboratory value of -432 ppm/K indicating the stability of the sensing system.

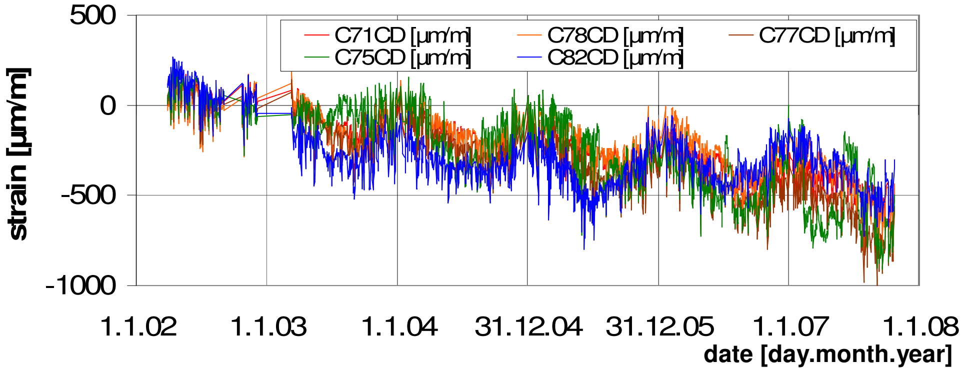

Figure 6. Strain development in section CD of the pylon (zone of its fixture).

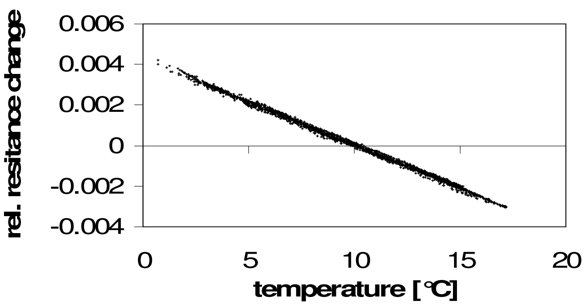

Figure 7. Temperature dependence of the dummy CFRP tendon.

5 CONCLUSIONS

A first full-scale overhead power line pylon made from HPC prestressed with pultruded CFRP tendons was realized in the year 2000 by SACAC Schleuderbetonwerk AG. This 27 meters high tubular pylon for the transmission of high voltages was produced by centrifugally casting technique with a concrete wall-thickness of merely 48 mm. It was therefore 40% lighter than a conventional steel-reinforced concrete pylon used for the same purpose. Lower costs for maintenance, transportation and installation with respect to conventional reinforced concrete elements make CFRP prestressed HPC economically interesting for this application.

The fundamental aspect of monitoring the durability of the CFRP prestress force by eliminating the problems of conventional surface intrusive measurements techniques like RSG was studied by a novel monitoring principle based on the electrical resistance measurement of the unidirectional carbon fiber reinforced epoxy tendons.

The strain evolution of the prestressing CFRP tendons was monitored for several years. The direct measurement of its resistivity allows using the prestressing tendon simultaneously as sensing element, which is an enabling technique. The functionality has been proven with laboratory experiments and the monitoring system shows good stability in the field application during the observation period and could confirm the calculated decrease of the CFRP prestress level due to the concrete creep and shrinkage under the central prestress. The monitoring will be continued in the near future.

6 ACKNOWLEDGMENTS

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