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Novel NDT-Techniques for Corrosion Monitoring and Fracture Detection of Prestressed Concrete Structures

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Abstract

This contribution deals with the practical verification of several innovative non-destructive monitoring concepts for the corrosion and fracture identification of tendons in prestressed concrete structures based upon a three level corrosion monitoring strategy. At first by means of *filament-sensors*, consisting of several parallel mounted thin iron filaments, the penetration of the depassivation front in the vicinity of the tendon can be monitored. Furthermore the *Electromagnetic Resonance Method* in combination with *electromagnetic field strength measurements* is used for the detection and localization of prestressing steel fractures based upon microwave technology. Here the spectral reflection response resp. the modification of external measured field strength of the electromagnetic signal, coupled into one end of the tendon, is analyzed.

These novel measuring techniques were tested in numerous experiments at simple lab made test specimens as well as at prestressed concrete trial members. As a result, the potentials, limits and restrictions of an in situ-application of these methods will be discussed.

Résumé

Le sujet principal de cette publication est la vérification pratique des quatre concepts de surveillance innovateurs suivants pour l'identification de corrosions et de fractures des tendons dans des structures précontraintes les capteurs à filament, consistant en plusieurs filaments fins en fer montés parallèlement en profondeur servant à saisir le cheminement du front de dépassivation dans le voisinage du tendon et la réflectométrie électromagnétique à hautes fréquences sur la base de mesures de résonances électromagnétiques en combinaison avec l'enregistrement électromagnétique du champ. On analyse ici la réponse de réflexion spectrale d'un signal électromagnétique à large bande couplé à une extrémité du tendon.

Ces nouvelles techniques de mesure ont été testées lors de vastes et de nombreuses expériences avec de simples éprouvettes en laboratoire ainsi qu'avec des membres en béton précontraint et en partie avec des ouvrages réels. En conséquence, les potentiels et les restrictions d'une application in situ de ces méthodes ont été élaborés.

Keywords

non-destructive testing, condition assessment, corrosion sensors, tendons, durability.

1 Introduction

Corrosion influences at prestressed bridges and substructures may impair the structural safety, serviceability and durability of tendons in prestressed concrete structures. Therefore, the objective of the condition assessment of tension members has to be the timely and reliable detection of existing faults and defects, as e.g. tendon voids, corrosion attack and fractures of the steel elements. For an objective early diagnosis of corrosion damages at tendons the condition monitoring and control by means of non-destructive inspection, testing and measuring techniques (NDT) is predestinated. Besides the inspection also the Structural

Health Monitoring (SHM) of the critical areas (hot spots) is achieving more and more importance. For corrosion monitoring of the corrosion state of tendons the "traffic-light" principle can be adopted, [1]. Here the colors have the following meaning:

–*green*: no corrosion, no measures have to be taken into account
–*yellow* (warning value): measures are required at the next regular maintenance date and
–*red* (alarm value): heavy corrosion or fractures exist, an immediate campaign is required.

For the corrosion assessment according to the phases of steel corrosion in concrete three monitoring levels can be defined, [2]:

–*1st initiation phase* (incubation phase until start of corrosion by depassivating of steel)
–*2nd deterioration phase* (induction phase, corrosion progress) and
–*3rd final failure state* (fracture) of the steel element.

Within the 1st monitoring level corrosion influenced parameters (e.g. moisture, Cl^-, pH-value, temperature) are measured by chemical sensors. By the interaction of these parameters an analysis of corrosion condition can be carried out. Further dummy sensors ("watch dog sensors") are used, where the corrosion of small corrosion cells or probes can be directly monitored. In the destruction phase investigations by means of non-destructive testing and measuring techniques (NDT) of the 2nd or 3rd monitoring level are conducted. The specified scheme and measurement tools can be combined to a corrosion monitoring strategy, cp. [1].

This paper will report on the development, testing and application of novel corrosion monitoring techniques for P/C-structures based upon smart filament corrosion sensors and electromagnetic measuring methods.

2 Filament-Sensors for Corrosion Monitoring – 1st Monitoring Level

With a novel, patented filament-sensor type, consisting of a single wire or of several, parallel arranged, 0.065 up to 0.5 mm thin iron filaments, the risk of corrosion can be monitored, [3]. If the depassivation (chloride or carbonation) front reaches the sensor the thin iron wires will corrode usually very fast. The corrosion-induced rupture of each filament causes a significant step like rise of the measured ohmic sensor-resistance. This effect easily can be measured e.g. by a standard ohmmeter or by a resistive bridge circuit.

Fig. 1 shows some prototypes of the filament-sensor. By grouping of several parallel wires one data channel is required and a deep dependent information can be achieved. For signal amplification at each wire a miniaturized serial Surface Mounted Device (SMD)-shunt resistor is implemented, [4]. The resistance R of a sensor with n wires can be estimated to:

$$\frac{1}{R} = \sum_{i=1}^{n} \frac{1}{R_{wire,i} + R_{shunt\ resistor,i}} \, . \qquad (1)$$

For the subsequent borehole instrumentation, a profiled prefabricated double-semicircular and dense mortar cylinder made with ribs and grooves for the protection of the wires was designed, cp. Fig 1. By the profiling also a good bond to concrete can be ensured. This sensor will be installed into a drill hole by a shrinkage-compensated grout of very small thickness. The plastic board with the two measuring cable connections is arranged between two semi-circular mortar cylinders. The remaining excavation and finally the front side of the sensor at the concrete surface will be sealed by a fluid epoxy-resin. Fig. 2 shows exemplary measuring results of two post mounted sensors at the prestressed trial bridge "Concerto".

Also a cascade of several single filament sensors connected in parallel and installed at different depth and positions can be used as an distributed filament-sensor type.

The general testing of functionality, applicability, characteristics and dependences of the new sensor concept have been performed at small mortar pieces in various lab tests as well as at real-sized concrete members. The main findings can be resumed as follows, [3,4]:

- Under alkaline, chloride free conditions corrosion of the sensing wires never occurred.

- The effective corrosion time until the fracture is linearly increasing with the cross section of the iron wire. At thicker single wires also the progress of corrosion before the fracture occurrence can be estimated.
- In axial compression and tensile splitting test of concrete cubes no significant change of the sensor resistance until crushing has been determined.
- The sensor shows a strong temperature dependence only if all sensor wires are broken. This can be used as a second criterion for corrosion detection.
- The conductivity of concrete, i.e. the moisture and salt content, has a stronger effect to the sensor resistance of a multi-wire sensor. But this does not affect the data interpretation. The failure of a single wire is a very clear signal even in good conducting NaCl-solution.
- The sensor performance can be impaired by voids, cracks and impressed currents.
- The sensors generally showed a good conformity with conventional macrocell corrosion sensors (anode ladder system) and with the chloride profile of concrete.

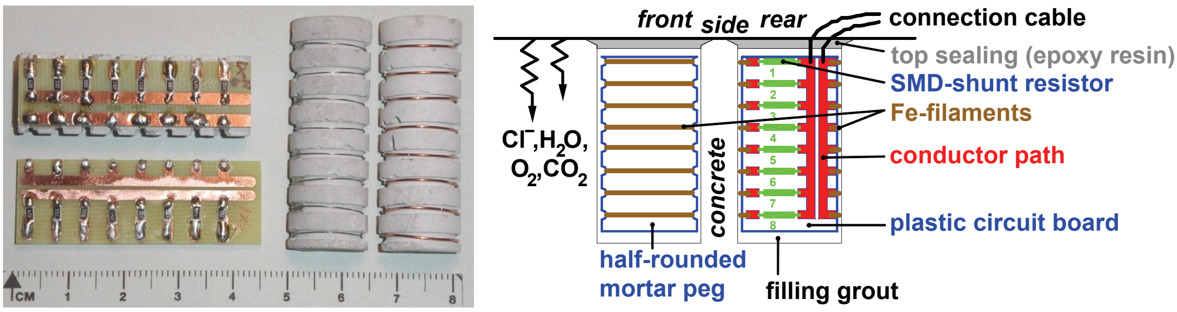

Figure 1. *Front and reverse side of prototypes of 8-wire filament-sensor with prefabricated mortar pieces; two semicircular sensors can be installed together in one drillhole*

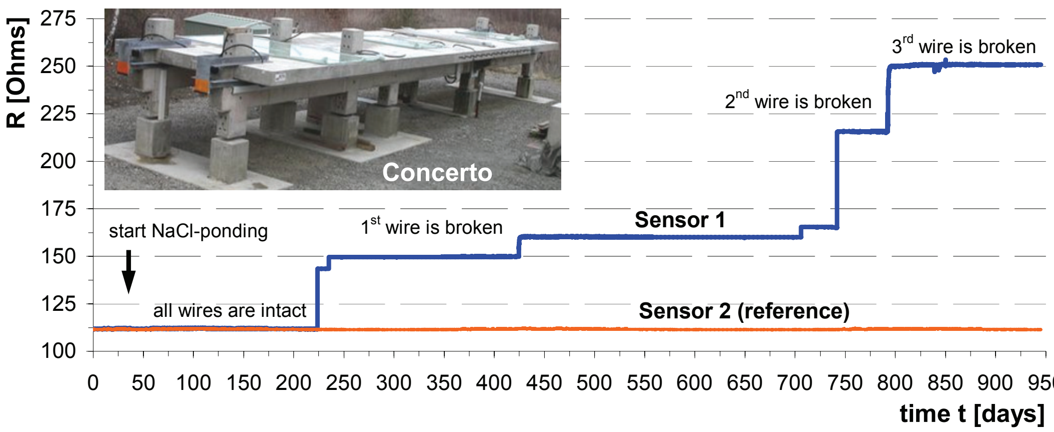

Figure 2. *Measured sensor resistance R of two subsequent installed 8-wire filament sensors with 0.065mm thin iron wires installed in the slab of the 18.5m long trial bridge "Concerto" (see photo), only sensor 1 has been exposed to 0.5mol NaCl-solution*

The filament sensor can be characterized acc. to the experience of five years as a robust, small sized calibration free miniature-sensor with a simple design, easy measuring procedure and very cheap instrumentation. It is sensitive to early stages and the progress of corrosion, shows no temperature dependence and works also in frost periods. As a "watch dog corrosion sensor" it offers an universal application for corrosion monitoring or sporadic measurements of R/C- and P/C-structures and also for post-installation.

The actual research is focussing on the implementation of wireless microsystem interrogation technology at the filament-sensors by means of MEM- and RFID-modules.

3 RF-Electromagnetic Resonance Measurements (ERM)-3rd Mon. Level

The Electromagnetic Resonance Method is a reflection measurement technique for the detection and localization of steel fractures in prestressed tendons and steel cables. The basic idea of this method is to consider the prestressed steel as an unshielded resonator situated in an electromagnetically lossy material (e. g. concrete). An electromagnetic wave of variable frequency is coupled into one end of the tendon, as depicted in Fig. 3. By scanning the reflection coefficient S_{11} over a wide-band spectrum by a vector network analyzer (NWA) resonance frequencies of the tendon are recorded. The (broken) length of the tendon l is inverse proportional to the spacings Δf between two adjacent resonance frequencies (cp. Fig. 4) and to the dielectric constant ε_r of the surrounding medium as shown in following equation:

$$l = \frac{c_0}{2 \cdot \Delta f \cdot \sqrt{\varepsilon_r}} = \frac{150}{\Delta f\,[\text{MHz}] \cdot \sqrt{\varepsilon_r}}\,[\text{m}], \qquad (2)$$

where c_0 is the vacuum speed of light. The simplified Eq. 2 is based on an ideal open-loop characteristic at the end of the steel wire. In reality there is an additional parasitic capacity to the ground potential. Hence, the measured spacings Δf are ca. 3 to 5 % smaller than the real values, [5]. For the evaluation of the correct strand's length we have developed a procedure for an in-situ determination of the real dielectric constant ε_r of the surrounding media (e.g. by means of radar measurement or by using dielectric coaxial sensors).

For the Radio Frequency (RF)-measurement the following influences are important:
–the position and geometry of the prestressing elements as electrical conductors
–the properties of the surrounding material (grout, concrete) and
–other defects (grouting voids, flaws and steel notches, corrosion and fracture at cables).
The interference of these influences complicates the interpretation of measured data.

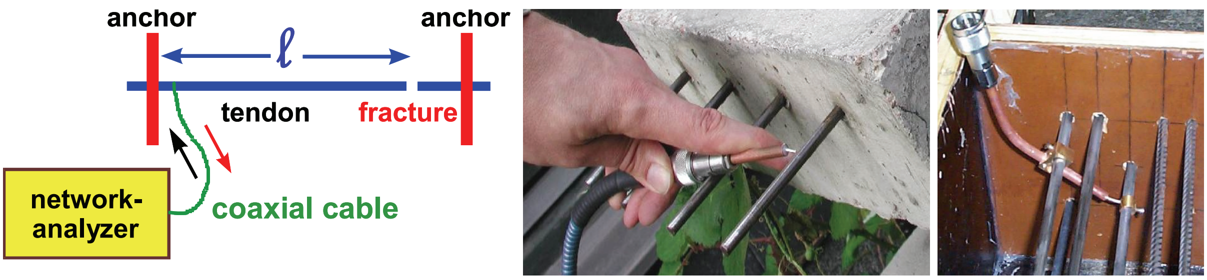

Figure 3. *ERM: Measurement principle and external resp. internal coupling adapters*

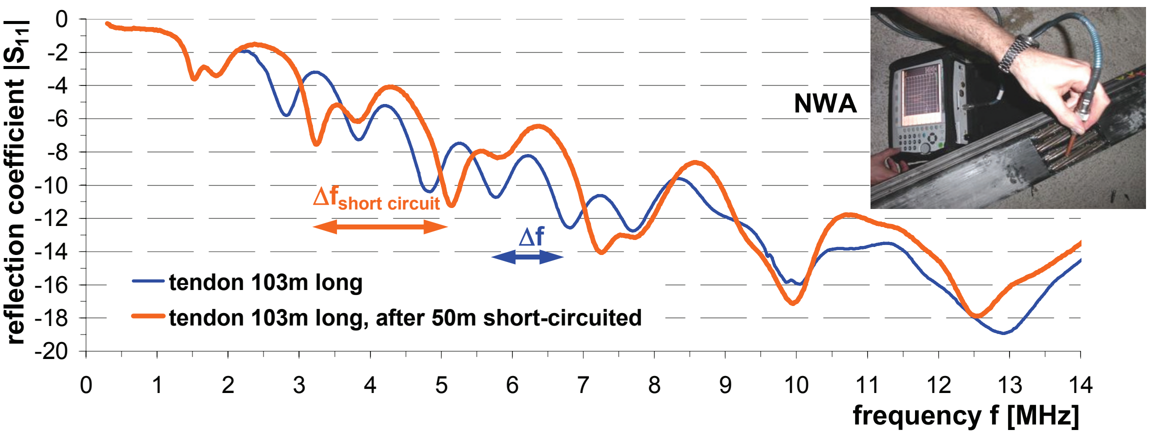

Figure 4. *In-situ-ERM-measurement at a 103m long external bridge tendon: measured reflection coefficient $|S_{11}|$ of an unbroken strand with and without electric short circuit after 50m simulating a local fracture; the photo shows the measurement configuration*

Derived from the measurements at lab-made members and from the first applications at real structures the following concluding remarks can be drawn:

- The ERM is appropriate for the assessment of ground anchors, external and electrically isolated tendons as well as monostrands, cp. Fig. 4.
- Due to the electrical interaction (short-circuits, electromagnetically coupling, corrosion currents) at real structures the measured reflection data are partly very complex. The variation factor of the determined differences Δf for each measurement can serve as an indication for the occurrence of electrical, geometrical or material anomalies.
- For P/C-elements with a large steel excess length a total reflection at the interface air to concrete occurs. This can be used for injection quality control e.g. at ground anchors.
- Fractures cannot be detected reliably in wet concrete (high RF-signal dampening) or if a continuous / multiple contact between the prestressing steel and the duct, rebars etc. exist.
- Corrosion induced crevices at single wires were usually detectable at lab specimens by a shift of the resonances, [2]. However, the signal modification due tor corrosion is insignificant from practical point of view.
- In an exemplary experiment the correlation of the ERM-reflection responses with a local void and moisture or salt penetration was obtained. The local change of the permittivity ε_r due to these anomalies cause a modification of characteristic cable impedance.
- The RF-measurement at a thin iron wire in the vicinity of the tendon is inadequate for corrosion assessment due to the high ohmic steel resistance and the high signal dampening in concrete. The fractures of the wire were hard to detect. However, favorable is the installation of an isolated copper cable as reference line besides the steel elements.

The Electromagnetic Resonance Method can be considered as a supplement to the existing magnetic fracture detection methods. A major advantage is that it sometimes allows the inspection of tendons in cases, in which the magnetic methods cannot be applied, e.g. at anchors. Main advantages of the ERM are that no walking along the tendon is required and that the access is only needed at one point of a tendon.

4 Electromagnetic Field Strength Measurements – 3rd Monitoring Level

Each AC-carrying electrical conductor is surrounded by an electromagnetic field. The generated electromagnetic field (radiation) can be used for the fracture diagnosis at prestressed steels. After feeding an electromagnetic standing wave into one end of the tendon, at the fracture position a partial or total reflection of the RF-signal occurs. Consequently the fracture location can be identified by the local drop of the magnetic or electric field strength which can be measured by external scanning by means of a field meter. Because of the same test set-up this method can be regarded as an enhancement resp. supplement of the ERM-technique.

This principle was tested at a hollow slab with severed prestressing steel elements. The RF- signal was generated by a network analyzer. The electric and magnetic field strength was measured by a handheld broadband field meter, type Narda NBM-550. The measured data in Fig. 5 show a clear drop of the electric field strength E at the steel fracture position for shortwave frequencies. This was observed for the magnetic field strength H as well.

Other tests and the experiences from ERM indicate that also at the interface from concrete to a void or to other concrete anomalies in the steel a partly or even the total reflection of the microwave signal occurs. It's conceivable that this effect also can be used for the identification of concrete defects. Here further investigations are needed.

The field density measuring technique represents in combination with ERM a good diversification tool for the detection and localization of steel fractures in concrete members.

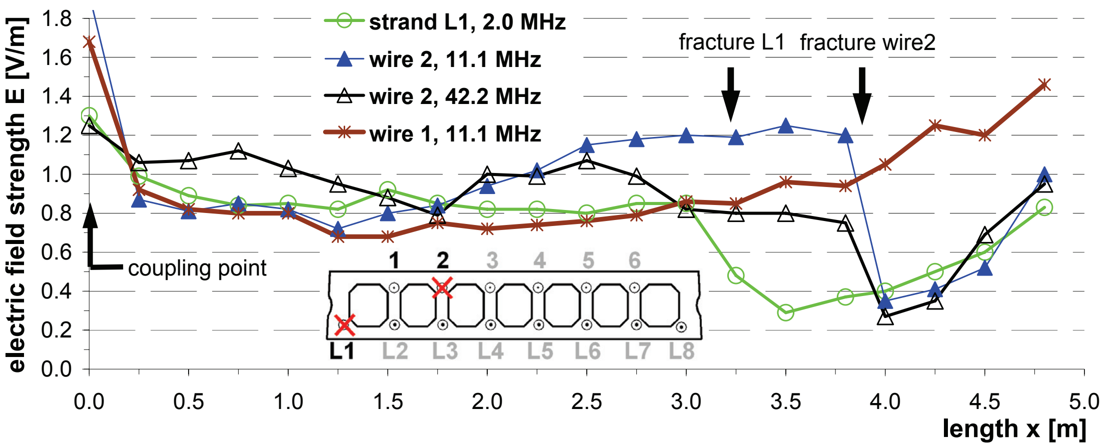

Figure 5. *Electric field strength data from the upper surface of a 4.8m long prestressed hollow slab with cross section of the member, only wire 1 is unbroken; the static field strength E_0 was determined to 0.05-0.10 V/m*

5 Conclusions

Based on a three step corrosion monitoring strategy, this contribution presents briefly innovative measurement techniques regarding corrosion sensing and fracture localization of prestressing steels for the assessment of even non accessible tendons in concrete structures. Very promising experimental results achieved with these novel methods are shown. A combination of the NDT-techniques can compensate partly inaccuracies and uncertainties of the individual methods. On the other hand some technical restrictions show that for new structures the prerequisites for monitoring must be ensured. The investigations for improving the measurement accuracy, effectiveness and further practical verification are going on.

Acknowledgements

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