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Long-Term-Monitoring of CFRP-cables over almost a quarter of a century

Peter ANDEREGG [1], Rolf BROENNIMANN [1], Urs MEIER [1]
[1] Empa, Duebendorf, Switzerland

Contact e-mail: peter.anderegg@empa.ch

ABSTRACT: A safe use of traffic infrastructures like bridges has to be guaranteed during the whole service time. Increasing number and weight of vehicles are a burden for these objects. Implementing structural health monitoring aims to detect evolving critical deviations in timely manner. In particular novel construction materials with limited knowledge of their long-term behavior should be surveyed.

This contribution focuses on the long-term behavior of carbon fiber reinforced polymers for tensioning cables. Measuring systems were implemented on three different kinds of bridges. Essential is a reliable and long-term stable measuring system. For this purpose reference measurements in the laboratory and redundant 'in situ' data were performed to discriminate between change of the infrastructure object and sensing artefacts.

An overview is given of the data obtained on the bridges and in the laboratory from resistive strain gages, fiber Bragg grating sensors and displacement transducers, covering a period of almost a quarter of a century.

1 INTRODUCTION

Structural health monitoring (SHM) can be used to extend the safe use of traffic infrastructures or to obtain more information of the long-term behavior of novel construction materials (Del Grosso et al, 2002; Harik et al, 2012). Implementing long-term monitoring systems help to verify the stability of critical parameters. Carbon fiber reinforced polymers (CFRP) for tensioning cables and their long-term behavior is of interest – especially their anchorage system is important (Meier et al, 2012 and 2015). For this purpose measuring systems were implemented on three bridges: a stay cable bridge, a steel-concrete composite bridge and a retrofitted reinforced concrete bridge. In all three bridges CFRP-wires are used for the cables. The earliest measurements were performed in April 1996, so performance records are available for a time period of over 23 years not only for the sensors but also for the whole measuring chain.

Compared with the long infrastructure lifecycle of many decades, a sensor lifetime is usually much shorter and components or sensor systems have eventually to be replaced over the monitoring period. Essential is a reliable and long-term stable measuring system (Anderegg et al, 2014 and 2018; Habel et al, 2005). Reference measurements not only in the laboratory but also on the infrastructure have been carried out over the same period. The collected data are essential to discriminate between change of the infrastructure object and sensing artefacts.

The applied sensors are based on resistive strain gages (RSG), fiber Bragg grating sensors (FBG) and linear variable differential transducers (LVDT). The reference data allow quantifying measurement uncertainty, stability and reliability of long-term measurements including the fact that some sensors failed, are suboptimal or are influenced by the environment.

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2 STORCHENBRUECKE, WINTERTHUR (SWITZERLAND)

The cable-stayed bridge Storchenbruecke was constructed in 1996 and was the first bridge with CFRP-cables. It has a length of 120 m and is crossing several railway tracks. 22 cables are steel cables, two were made of CFRP. Each of them has a length of 35m and consists of 241 CFRP-wires with a diameter of 5 mm. The mean load of the cables is approximately 1000 kN (stress level 211 MPa) and therefore relatively low (Figure 1).

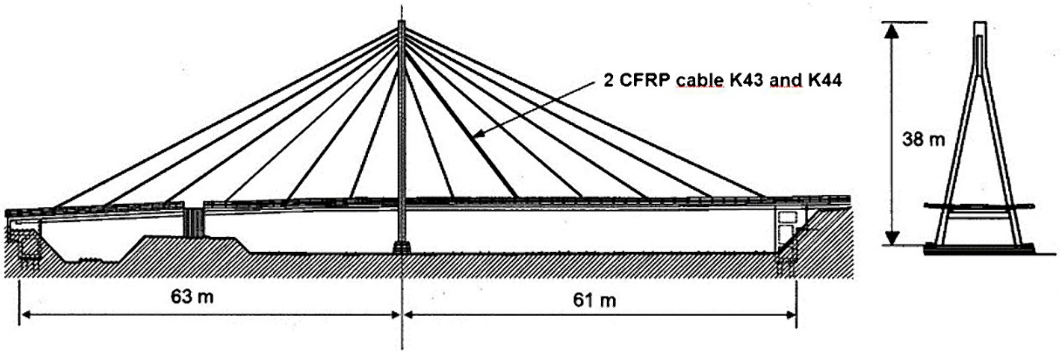

Figure 1. Layout of the cable-stayed bridge Storchenbruecke with the two CFRP-cables

The monitoring system includes nine RSGs, two fibers each containing seven FBGs, four displacement sensors and temperature and humidity sensors. The load results in strain levels of about 1200 µm/m on each CFRP-wire. Strain is measured by means of surface adhered RSGs and FBGs. To measure the pull-in of the CFRP wire bundle into the anchor head a displacement sensor based on a RSG equipped bending spring was developed and such springs sensors were installed in the upper and bottom anchor heads. An identical sensor was installed as a reference in the laboratory. The axial thermal expansion of the CFRP-cables is negligible compared to the steel cables with 11 ppm/K. Hence changing ambient temperature results in load redistribution between the steel and CFRP cables. The range of temperature induced load variation corresponds to about 25 % of the tension in the CFRS cables. Figure 2 shows the three-hour mean values of the cable force obtained from the RSG-measurement of a typical year (2006).

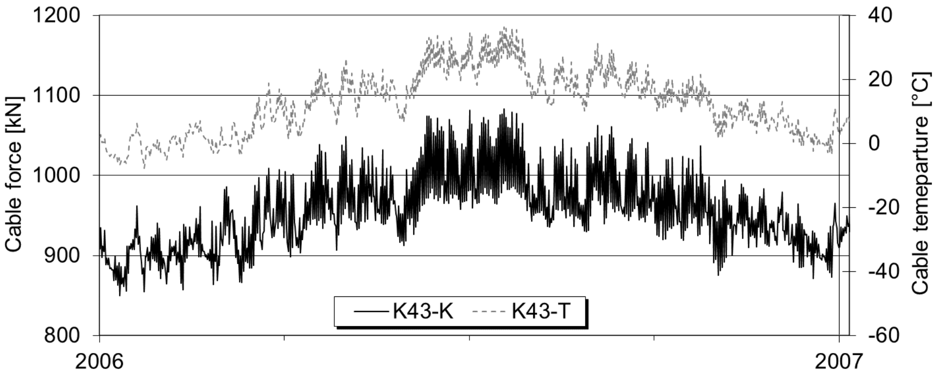

Figure 2. Three-hour mean values of the force on cable K43 obtained from the RSGs

In Figure 3 the strain measurements with RSGs and FBGs on cable K43 and K44 are compared for a time period of 22 years. The data from these completely independent measurements correlate strongly and, as explained before the measured load is mainly a function of the temperature.

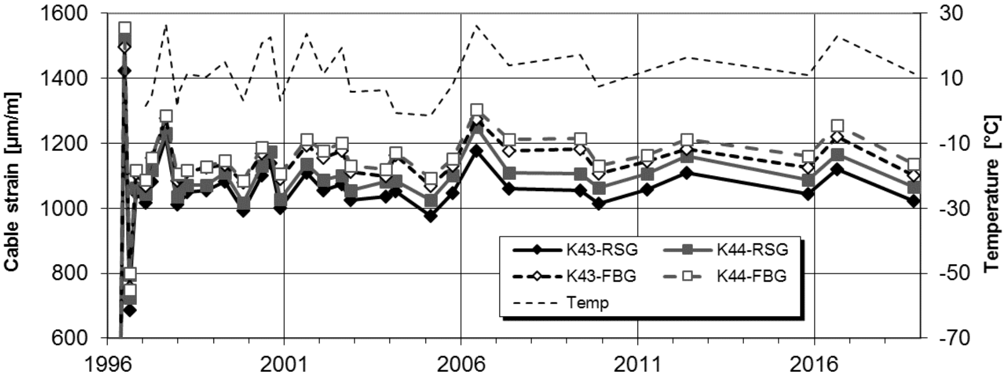

Figure 3. Comparison of the strain measurements with RSGs and FBGs on cable K43 and K44

At the time of installation only little information of the long term stability of FBG was available (Broennimann et al, 1998; Nellen et al, 1997; Maaskant et al, 1997; Tennyson et al, 2001; Majumber et al, 2008). Therefore the installed cables were equipped with FBGs adhered to unloaded CRFP wires in either un-strained or pre-strained states. The pre-strain level of the pre-loaded fibers is around 2500 µm/m. This is twice the strain of the FBG on the active wires. A loss of strain caused by drift or debonding would be an indicator for a measuring error. However, the scattering of the seven FBG-dummies shows no temporal dependency within the measurement accuracy. It can be derived that the average drift over a period of 22 years of the complete measuring chain is well below 1 µm/m per year. Figure 4 shows the difference between the RSG- and FBG-measurements on the cables K43 and K44. Considering the small FBG-drift the remaining drift of approximately 3 µm/m per year must be attributed to the RSGs [Herrmann et al, 2012; Espion et al, 2000).

5 of 18 RSGs failed within 22 years. A lightning in May 2003 caused probably three of the failures. On the other hand, all 14 FBGs are still operational.

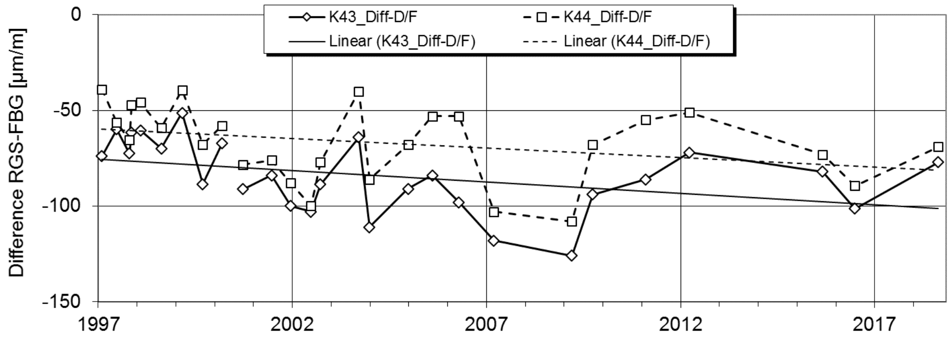

Figure 4. Difference between RSGs and FBGs on the cables K43 and K44

The pull-in of the CFRP parallel wire bundle into the anchor head after the tensioning of the cables is around 7 mm. Within the monitored 22 years, the pull-in increased uniformly by about 0.1 mm per year (Figure 5) with a tendency to slow down. The process is unidirectional and does not correlate with temperature. An identical reference sensor in the laboratory shows after an initial settling time a linear drift of about 2 µm per year verifying the high long-term stability of the sensing system. Since the measurements on the bridge started several months after installation this settling effect is not relevant for the long-term behavior and is below the required long-term stability.

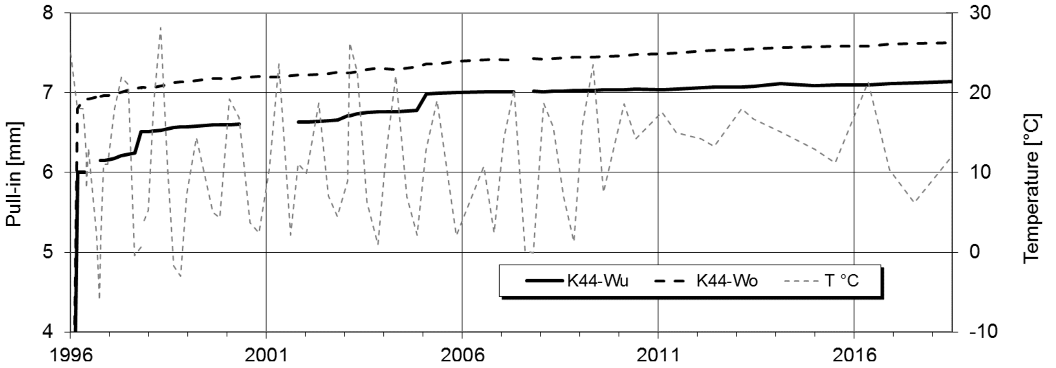

Figure 5. Pull-in of the CFRP-wires into the upper and bottom anchor of cable K44 over 22 years

3 BRIDGE "KLEINE EMME", LUCERNE (SWITZERLAND)

The bridge “Kleine Emme” is a steel–concrete-composite bridge for pedestrians and bicycles and has a length of 47 m. It was constructed in 1998 and had to be dismantled in 2016 due to the change of the traffic concept. For the pre-tensioning two CFRP-cables with 91 wires with a diameter of 5 mm were installed in a steel tube under the bridge deck (Figure 6). Each cable was pre-stressed with a load of 2400 kN (stress level 1343 MPa).

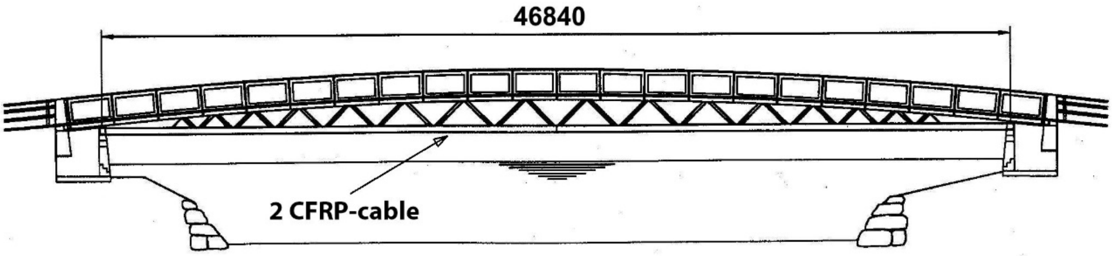

Figure 6. Layout of the bridge “Kleine Emme” with two CFRP-cables under the bridge deck

The pre-stressing load corresponds to a strain level of about 8'200 µm/m. This high strain level required an anchor head design which releases the strain in the wires gradually. To verify the design the strains had to be monitored not only in the free cable part of the cable but also within the anchor head. For this reason the FBGs were embedded in the CFRP-wires during the pultrusion process. This allowed to record the local strains inside the anchor head and demonstrated the continuous decay of the axial strain.

Since RSGs attached on the CFRP failed during the pre-tensioning process and during operation, additional RSG-full-bridges were retrofitted on the steel sleeve halves one year after the bridge assembly. Figure 7 gives an overview of the installed sensors. The three-hour mean values of the RSG-strains and pull-in were recorded. In addition redundant manual measurements of RGSs and FBGs were performed at irregular intervals.

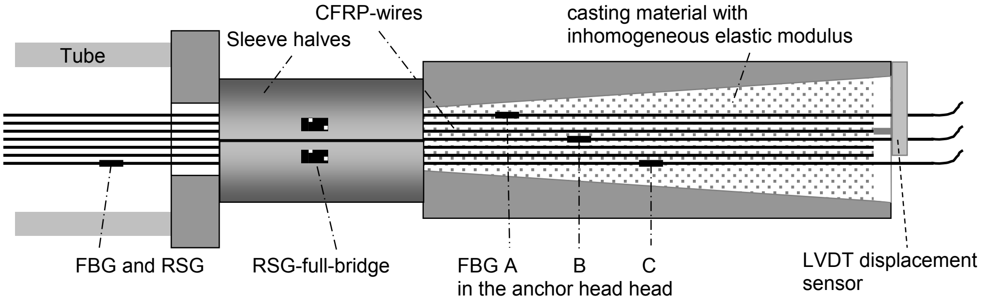

Figure 7. Cross section of the anchor head with the adhered sensors on the cable and the sleeve halves

A comparison between the calculated forces obtained from the manual strain measurements with FBGs and RSGs on the CFRP-wires and RSGs on the steel sleeve halves correspond within a bandwidth of 1 % of the 2400 kN load derived from the oil pressure of the tensioning machine.. In Figure 8 the pull-in measurements for cable K1 and K2 are shown. After pre-tensioning and a short settling time the pull-in with about 10 µm over 20 years is very low. This is surprisingly small compared to the uniformly pull-in increase on the Storchenbruecke with only a seventh of the wire load. It can be interpreted in a way that with higher loads the long term settling is faster achieved.

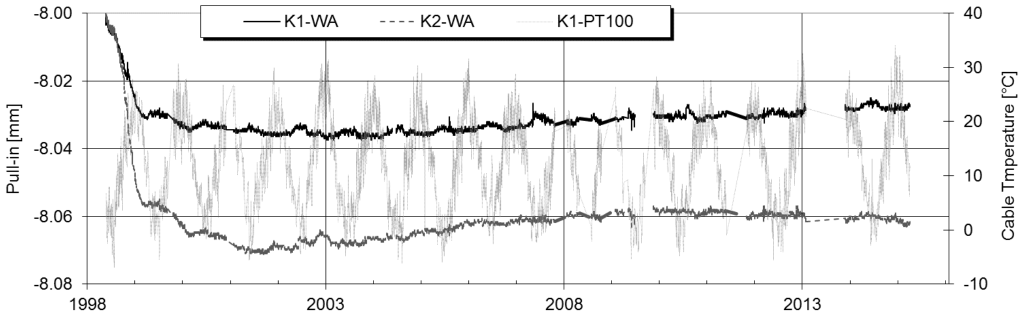

Figure 8. Pull-in of the CFRP-wires into the anchors of the cables K1 and K2

As mentioned above this bridge had to be dismounted. First, the cable load was released and the two cables were removed. It was of great interest to measure the strains with RSGs and FBGs during this process. The strains measured with RSGs and FBGs on the CFRP-wires in the free part show the same behavior. Figure 9 shows the result of the FGBs in the anchor head. The FBG in section A is closest to the load side of the cable. Therefore it has the highest strain level. It shows the fastest strain decay during load release and reaches the release strain even before the FBGs in section B and C show a significant strain reduction.

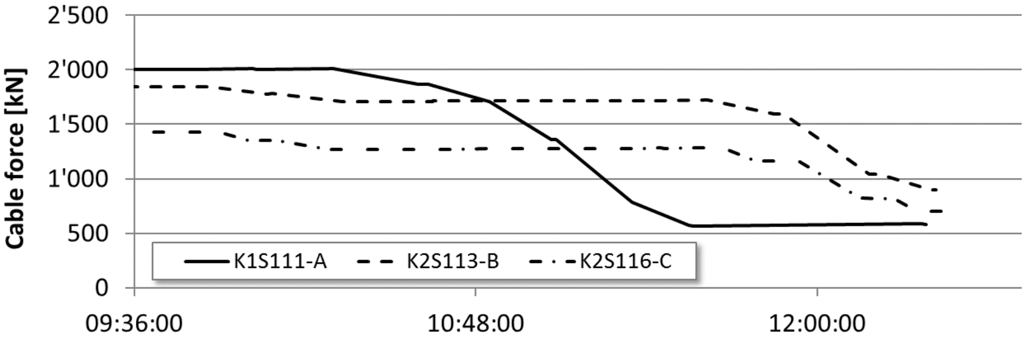

Figure 9. Relaxation in the anchor head measured with the FBGs on positions A, B and C

Since constant strain levels of around 9000 µm/m are very high for RSGs a CFRP wire was equipped with three RSGs for a reference long-term laboratory test. The wire was loaded with a constant force of 32 kN. The three loaded RSGs and the three unloaded dummy RSGs show a high stability. Because the CFRP wire is rigidly connected to the testing machine its temperature dependent elongation dictates the thermal expansion of the wire. Therefore the chosen RSG-temperature coefficient of 11 µm/m/K for steel is the correct compensation. Consequently, the dummy RSGs are overcompensated and show a temperature dependence of -11 µm/m/K as expected. The decrease of the strain over the time is an overlay of relaxation of the wire anchoring, of the testing machine, the load cell and the RGS drift (Figure 10). The strain to load ratio indicates a standard deviation of 0.5 µm/m/kN or around 0.2 % of the load over 20 years. This confirms a very good long-term laboratory stability of RSGs on CFRP-wire applications. The lack of load cell data around the year 2009 is due to a replacement of an amplifier. The change of the strain and force level is a result of a new tensioning after a location change of the testing machine.

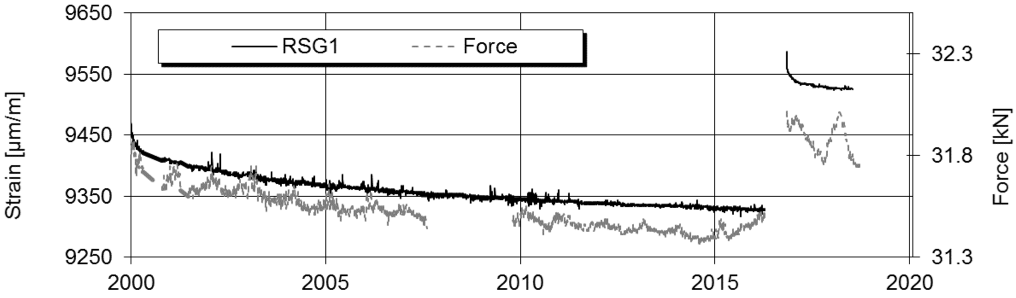

Figure 10. Strain and force development over the time of almost 20 years

After dismounting of the bridge in 2016 and disassembling of the cables an investigation of the failed RSGs on the CFRP-wires was carried out. After carefully removing the protective coating on the RSGs a visual and electrical inspection showed, that two of three RSGs on both cables K1 and K2 had broken connecting leads. On each cable one RSG did not show visual defects and a resistance of about 122 Ω was measured (initially about 120 Ω). The Dummy-RSGs did not show any defects. Obviously the precautions taken during application of the RSGs with respect to the high expected strains were not sufficient. However the reason for the failure of the active RSGs is assumed to be twisting of the wires and relative movements between the wires within the wire-bundle during tensioning. Within the monitored time 8 of 21 FBGs failed, all 6 RGSs on the CFRP wires failed (4 after tensioning, 2 later on). None of the 4 RSG-full-bridges on the steel-sleeves failed and none of the two pull-in sensors.

4 BRIDGE "SUL RI DI VERDASIO", CENTOVALLI (SWITZERLAND)

The third bridge is a 70-m-long reinforced concrete bridge. The initially installed steel post-tensioning cables partially corroded. Therefore, the bridge was retrofitted with four additional CFRP-cables (Figure 11). Each cable consists of 19 CFRP-wires with a diameter of 5 mm and is pre-loaded with 600 kN, which corresponds to a stress level 1608 MPa or a strain of about 9700 µm/m.

Here, no sensors have been attached on the CFRP-wires. To monitor the cable force RSG-full-bridges were installed on the sleeve-halves of all eight anchor heads on both sides of the bridge. The pull-in of the CFRP wires into the anchor head was measured manually with a caliper gage.

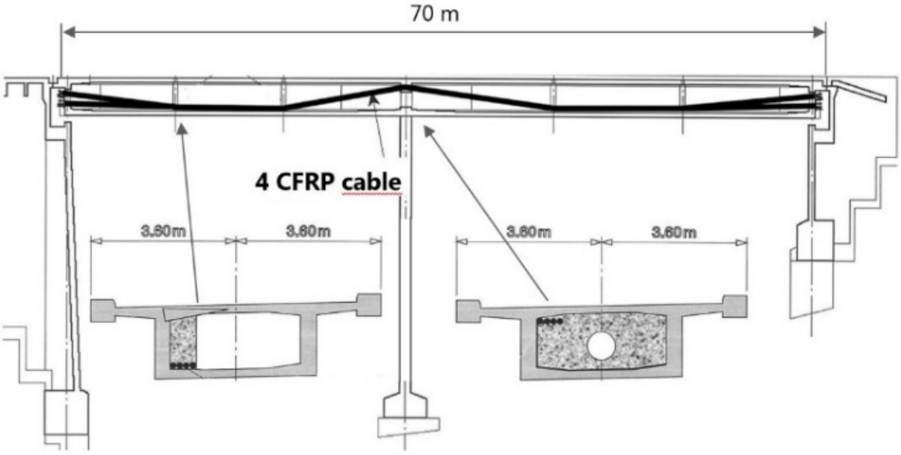

Figure 11. Cross sections of the retrofitted bridge "sul Ri di Verdasio"

Similar to the bridge 'Kleine Emme' the tensioning of the cables produces a compression force in the sleeves. Ongoing completion of the bridge with guardrails and pavement induced a small load increase during the first year. The measurement on one anchor showed a strong strain signal increase during the first year clearly deviating from the other measurements. A possible cause is discussed below. The RSG-measurements after tensioning shows primarily the force change due to the temperature span of around 30° C (Figure 12). The tensioning of the cables to approximately 600 kN produced initial pull-ins between 2.5 to 3.5 mm and remained on this level within 0.1 mm during the whole monitoring period. As for the bridge "Kleine Emme" this stability is remarkable. No sensors failed since the installation in the year 1998.

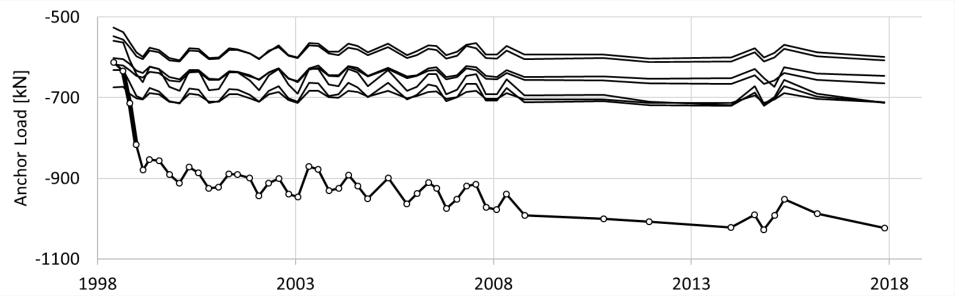

Figure 12. Anchor load received from measured strain signal on the steel-sleeves for all eight anchors

The strong increase of the indicated load on one anchor socket during the first year could not be explained concluding. The design of the tension measurement device was retrofit and had to be adapted to the existing situation. Initially performed tests under ideal condition of a centric load introduction showed a scattering of the results within 1 % of the load. But tests performed later on an equivalent load cell showed that even small deviation of ideal load introduction (off-axis, shear) can result in strong signal response, sufficient to produce the observed deviation.

5 CONCLUSIONS

The aim of this contribution is to give an overview of the challenges to maintain long-term monitoring systems over more than two decades. The given examples show that reliable long term monitoring is possible but requires a corresponding effort. The reported monitoring systems demonstrate the reliability over this long period, even when failures occur or sensors have to be replaced. The redundant sensor measurement as well as the laboratory tests, the technical knowledge and a careful installation of the sensors lead to a successful long-term monitoring.

6 ACKNOWLEDGEMENTS

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