SMAR 2017 – Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

SMAR 2017

An Innovative Deformation-Based System for Monitoring the Structural Safety of Stay-Cables

Martin Bimschas[1] and Walter Kaufmann[2]

[1] dsp Ingenieure & Planer AG, Greifensee, Switzerland
[2] ETH Zürich, Switzerland

ABSTRACT: After the occurrence of a corrosion-related stay cable failure at a Swiss pedestrian bridge from the 1960s, a similar cable-stayed pedestrian bridge was thoroughly investigated. While, based on a number of analysis techniques, it could be concluded that the stay cables in this second bridge were generally in a good condition along their free lengths, some uncertainties remained concerning the state of the cables in their upper anchorage zones where the cables intrude into the pylon. In order to avoid the risk of a sudden cable failure it was decided to install a permanent monitoring system aiming at detecting potential wire fractures in the upper anchorage zones. For the given task an individual new concept was developed and implemented. Being based on deformation measurements this monitoring system allows the reliable detection of wire fractures before a potentially critical state is reached.

1 INTRODUCTION

In the year 2007 a cable-stayed pedestrian bridge in the city of Basel, the so-called *Birskopfsteg* built in 1963 as the first structure of this type in Switzerland, experienced a partial failure due to the fracture of one of the, in total, 6 stay cables (see Figure 1). In-depth investigations of the dismantled cables, carried out at EMPA in the aftermath of this failure, showed that even 5 cables were showing significant signs of corrosion as a consequence of insufficient grouting of the PE ducts, and that this was also the cause for the eventual failure of one cable (Alvarez *et al.*, 2011).

Since the same type of cable-grouted duct system was used in another cable-stayed pedestrian bridge, namely the *Personenüberführung (PÜF) Oberwies* built in 1976 in the outskirts of Zurich, the bridge owner, the Federal Roads Office FEDRO, infrastructure branch Winterthur, decided to perform a detailed investigation on the state of its 8 stay cables (see Figure 2). Based on several types of probing and intensive testing, it could be concluded that grouting of the ducts and the related condition of the tendon wires here were much better than in the case of the *Birskopfsteg*. At the same time, these investigations could only be performed along the free length of the cables, whereas the potentially most critical parts close to the upper anchorage zones inside the RC pylon were not accessible to probing, leaving some uncertainty concerning the cable condition in this part.

In order to limit the related risk of a sudden cable failure in the upper anchorage zone, it was decided to install a permanent monitoring system that should allow the detection of potential fractures of wires before the subsequent failure of an entire cable. After a review of existing monitoring systems for this purpose, it was concluded that the development of an individual and novel deformation-based monitoring system would be most suitable for the given task. The concept and its implementation will be described in the following sections of this publication.

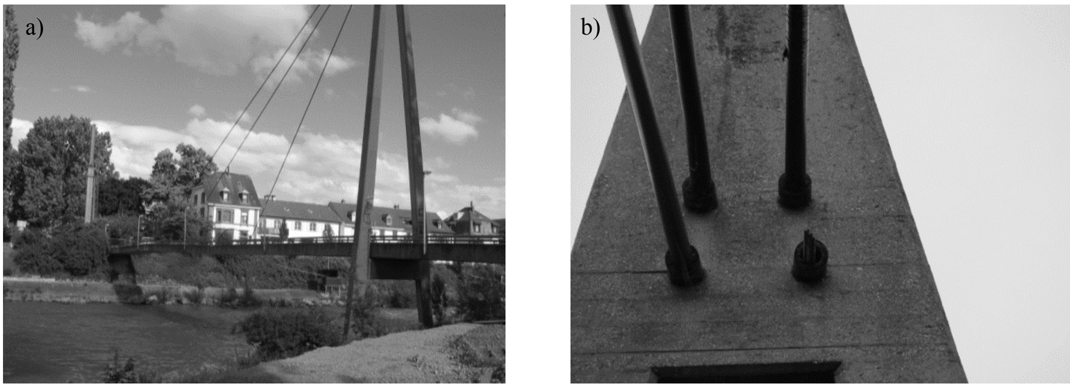

Figure 1. Birskopfsteg, Basel, (a) deformed superstructure after failure, (b) pylon with fractured cable (© Vollmer, 2007; taken from Alvarez et al., 2011).

2 CHARACTERISTICS OF PÜF OBERWIES

The two symmetrical spans of the pedestrian bridge under investigation, PÜF Oberwies, cross the 2 x 4 lanes of the national highway A1 (Figure 2.b). The total length of the superstructure is 64.8 m and its width is 4.26 m. The 8 stay cables consist of conventional BBRV tendons ($f_{p0.1k}$ = 1440 MPa, f_{pk} = 1670 MPa) inside grouted PE ducts. The long cables feature 55 wires of diameter $Ø_{wire}$ = 7 mm, while each of the short cables features 36 wires. The upper anchorages of the tendons are embedded in the concrete pylon (see Figure 5.a).

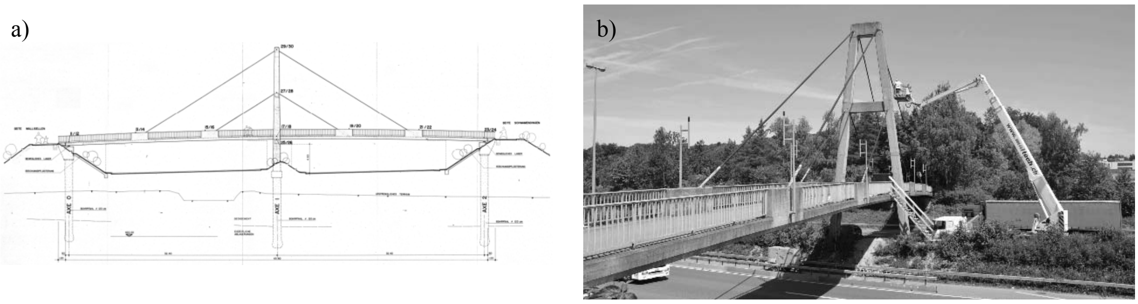

Figure 2. Personenüberführung (PÜF) Oberwies, Switzerland, (a) elevation and (b) photo during inspection of stay cables.

Under permanent loading the prestressing forces in the stay cables were determined by dynamic measurements as approximately 430 kN and 420 kN for the short and long cables, respectively, resulting in corresponding utilization factors of merely 25% and 16% in relation to the design resistance of the undamaged tendons. Under full design loading, cable forces of 890 kN and 814 kN were calculated using finite element analysis. In relation to the ultimate resistance of the cables this corresponds to utilization factors of 38% and 23%, respectively. This low level of utilization for the stay cables suggests that roughly more than 60% (short) or 75% (long) of the wires could fracture before a critical state is reached (assuming that the remaining unfractured wires are fully intact).

3 TECHNICAL CONCEPT OF MONITORING SYSTEM

Several different strategies for the monitoring of the stay cables were evaluated at the start of the project, including (among others) approaches based on acoustic emission (e.g. Fricker, 2010). Based on considerations of cost-effectiveness as well as reliability, and because the region of potentially expected wire fractures could be localized at the immediate vicinity of the upper anchorage zone of each cable, an individually developed deformation based measuring system was considered most suitable for a permanent, long time monitoring system in the present case.

The aim of this system is to detect potential wire fractures before a critical state of the stay cables is reached, that is, as long as the remaining, unfractured wires can still guarantee a sufficient structural safety. For this task it is beneficial that the degree of utilization of the stay cables is rather low. As a consequence, it is not necessarily important to detect every individual wire fracture, but it is more relevant to reliably notice a number of fractures that could be the start of a critical development. This holds in particular because the monitoring system was installed at a bridge age of 37 years, so that the potential number of previous wire fractures is generally unknown.

The general concept of the chosen system consists of measuring elongations of the suspected damage zone below the upper cable anchors by means of high resolution extensometers. With the assumption that the total force in a stay cable remains rather uninfluenced from fractures of individual wires, it can be concluded that the remaining, intact wires receive higher stresses – and thus strains – with an increasing number of broken wires. As the cables run in grouted ducts, the related bond between wires and grout causes the fractured wires to be reactivated over the bond length l_b (in a similar sense as in a lap splice, see Figure 3).

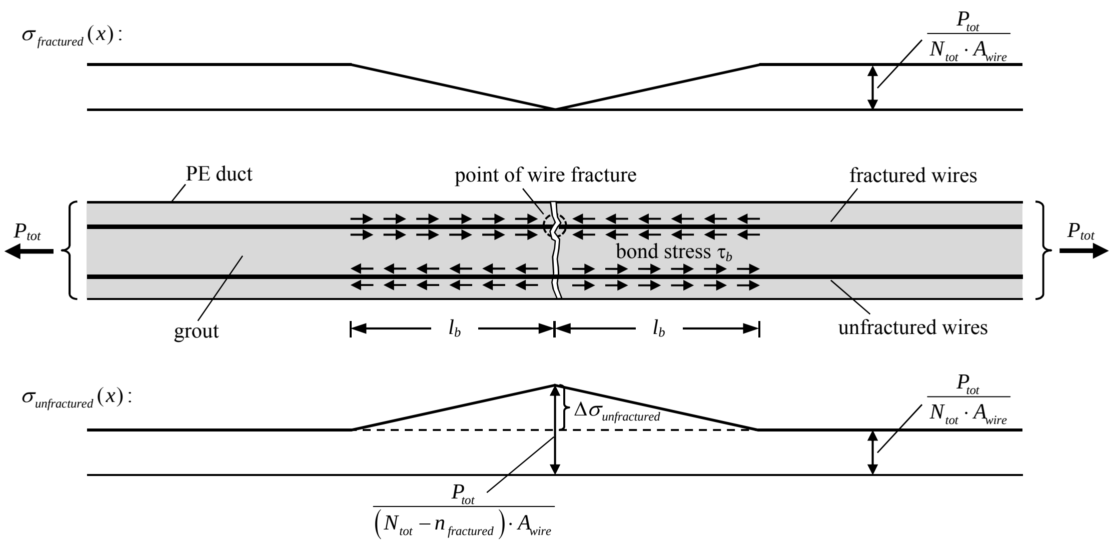

Figure 3. Cable stress distribution in the vicinity of local wire fractures; bond related interaction between fractured and unfractured wires.

At a distance of l_b from the point of wire fracture all wires of the tendons are thus equally stressed again. Therefore the stress increase $\Delta\sigma_{unfractured}$ in the unbroken wires is limited to a region of l_b at both sides of the fracture point. The corresponding additional strains $\Delta\varepsilon = \Delta\sigma/E_p$ create the local elongation of the cable that can be measured with the designated extensometers. The peak stress increase $\Delta\sigma_{unfractured}$ can be calculated using equation (1):

$$\Delta\sigma_{unfractured} = \frac{P_{tot}}{A_{wire}} \cdot \left(\frac{1}{N_{tot} - n_{fractured}} - \frac{1}{N_{tot}} \right) \qquad (1)$$

with $\Delta\sigma_{unfractured}$: Additional stress in remaining, unfractured wires of stay cable
P_{tot}: Total force in stay cable
A_{wire}: Cross-section of a single wire
N_{tot}: Total number of wires in stay cable (fractured & unfractured)
$n_{fractured}$: Number of fractured wires in stay cable

The actual bond length l_b and the detailed distribution of stresses $\Delta\sigma_{unfractured}(x)$ along l_b depend on the bond stress-slip behavior between the wires and the grout. For plain bars and wires the bond stress-slip behavior is generally characterized by a rather stiff initial phase due to adhesion and a subsequent more or less plastic phase related to friction (Rehm, 1961; Martin and Noakowski, 1981; Feldman and Bartlett 2005 & 2007; Bülte, 2008). Approximating this behavior with reasonable accuracy by a rigid plastic bond stress-slip law, a theoretical relationship between the stress increase $\Delta\sigma_{unfractured}$ and the local cable elongation can be deduced using the principles of the *tension chord model* (Marti *et al.*, 1998). By means of equation (1) furthermore a relationship between the number of fractured wires and the cable elongation can be developed.

Both relationships are evaluated in the two graphs shown in Figure 4. For the underlying quantification the plastic bond stress τ_b of the cold-drawn wires has been estimated according to Model Code 2010 (fib, 2013) as $\tau_b = 0.1 \cdot f_c^{0.5} \approx 0.55$ MPa (for good bond conditions and an assumed compressive strength of the grout of $f_c \approx 30$ MPa). From the results shown in Figure 4 it can be seen that for a small number of wire fractures only minor cable elongations occur. However, due to the hyperbolic characteristics of equation (1), a disproportionate increase of deformations develops with an increasing number of broken wires. As a result, a significant elongation of the cable may be expected before a critical state is reached.

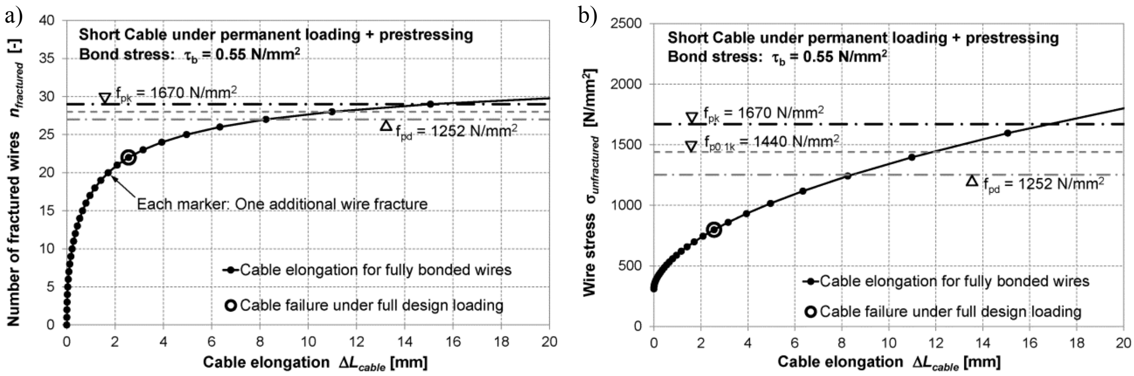

Figure 4. Cable elongation due to wire fractures: (a) relationship between number of fractured wires and elongation, (b) relationship between stress in unfractured wires and cable elongation.

This hyperbolic behavior may also be considered a beneficial aspect considering that the monitoring system is installed at a bridge age of 37 years. Any (small) number of wire fractures that may have occurred before its installation thus does not call the overall reliability of the system into question because a critical development can still be detected based on a progressive increase of deformations. This effect may be considered an advantage in comparison to, for example, an acoustic emission based system that only gives a count of broken wires after its installation without any further indication of the resulting condition of the cable.

A potential zone of insufficient grouting (with corresponding lack of bond) increases the length of additional stresses $\Delta\sigma_{unfractured}(x)$. While this influence adds some uncertainty to the quantification of the relationship between number of wire fractures and cable elongation, the increased cable deformations also improve the general detectability of broken wires. Disregarding a potential zone of insufficient grouting in the theoretical quantification is therefore conservative.

Since the level of bond stress τ_b is influenced by a number of aspects, a parametric study was performed covering, on the one hand, the reasonable range of τ_b values (as given in the literature) and, on the other hand, a variety of assumptions concerning the length of a potentially unbonded zone due to insufficient grouting. This study showed that, even for the most unfavorable assumptions concerning the bond behavior, a cable elongation of at least 1 mm would be expected before a potentially critical state of the cable is attained. Deformations of that magnitude can be measured reliably with the chosen monitoring system as described in the following section.

4 DETAILING AND INSTALLATION

In order to measure the cable elongations in the upper anchorage zone of the stay cables, extensometers with a resolution of about 0.01 mm were chosen. Taking all unfavorable secondary effects into account (e.g. due to fixation flexibility), it was considered that an effective precision of the measuring data of at least 0.1 mm must reliably be achieved in order to adequately cover the range of relevant cable deformations (Figure 4).

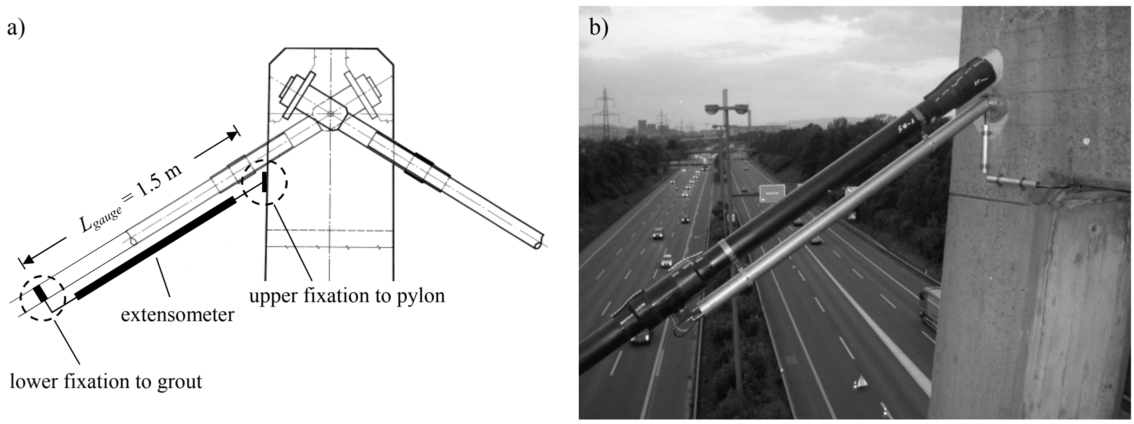

Figure 5. Fixation of extensometer: (a) schematic sketch and (b) photo of implemented solution.

The gauge length needs to span the entire potential influence zone of wire fractures. At the top it was decided to fix the extensometer to the concrete pylon as this is rigidly connected to the anchor of the cable. At the lower end it was conceptually not possible to attach the extensometer directly to the wires. Therefore it was chosen to apply the fixation to the grout as this is bonded to the wires. For this purpose the PE ducts had to be opened locally and needed to be carefully sealed again after the installation. Each extensometer is equipped with a built-in temperature gauge. An additional temperature gauge was installed to the surface of the grout at each lower fixation point that was later on covered by the restored duct.

The concept of the fixation, as well as a photo of its finished implementation, are shown in Figure 5. The suspected fracture zone is essentially located between the upper anchor plate and the surface of the pylon as this region could not be inspected. This entire zone plus approximately 1.5 m outside the pylon are covered by the monitoring system. The extensometer is protected by an external aluminum tube that is separately attached to the outside of the PE duct. All gauges are connected to a data logger that automatically sends all data to a webinterface via a GSM module. The various temperature sensors provide the basis for a temperature compensation of the deformation data, if necessary.

5 MEASURING DATA

5.1 Reliability and influence of temperature

The system was installed in the summer of 2013 and since then it is running properly without interruption. Measuring data are acquired once every hour. Two examples of data time series for a long stay cable are shown in Figure 6. On the left side (Figure 6.a/c) the hourly development of both deformation and temperature measurements are shown for a time period of 1 month. The temperature related variation during day and night can clearly be seen. The circular markers in both graphs indicate the measurement at 5:00 am every day. It can be seen that this early morning measurement is much more stable than the hourly data because any temperature influence is strongly reduced. For this reason, the 5:00 am measurements are taken as the relevant basis for the interpretation of the monitoring results (i.e. identification of potential wire fractures).

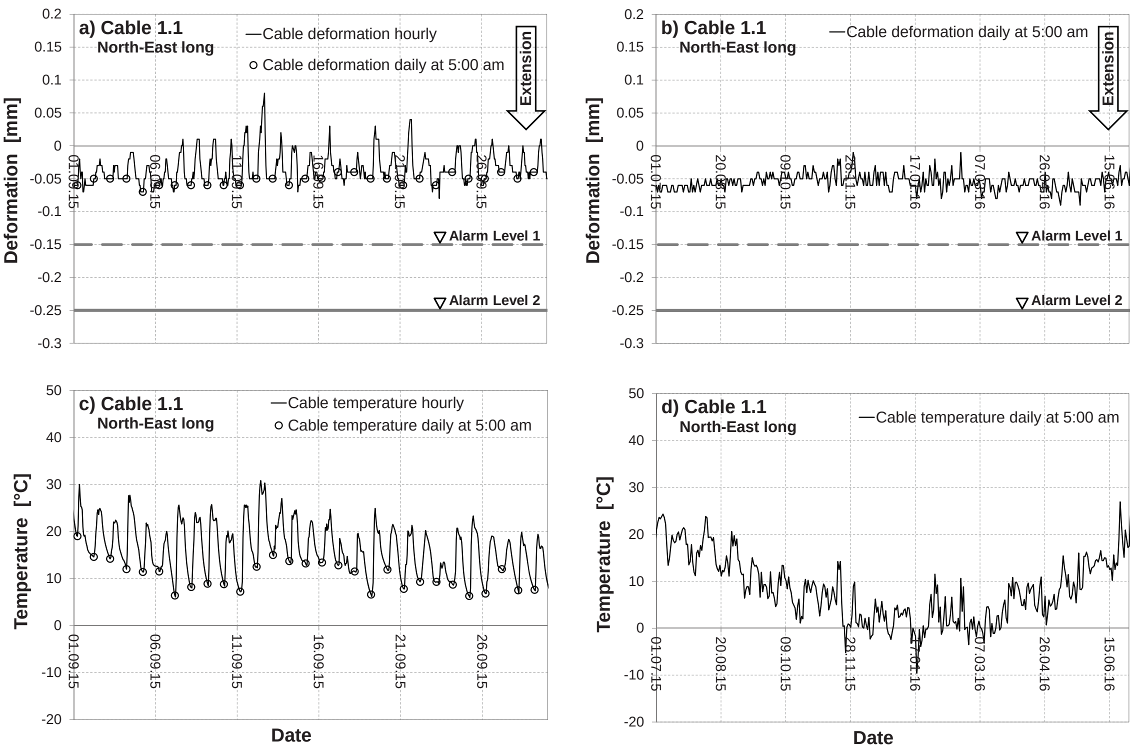

Figure 6. Deformations of cable 1.1: (a) comparison of hourly variability vs. daily measurements at 5:00 am; (b) development of 5:00 am measurements during 12 months; and (c), (d) corresponding cable temperatures.

The two graphs on the right side (Figure 6.b/d) show a series of daily 5:00 am measurements during a time period of one year. It can be seen that, despite significant temperature variations between summer and winter, the corresponding deformation data hardly vary and they also show very little scatter.

By more in-depth analysis of the data, complemented by detailed finite element analysis, it can be found that the hourly variation of the deformation measurements is primarily related to internal stress states within the bridge because the cables react faster to temperature changes than the rest of the (concrete) bridge structure. This effect does not occur with respect to the temperature variation between winter and summer because they develop much slower. Since at 5:00 am the entire structure (cables and concrete) has essentially the same temperature, the measurement at this time is uninfluenced by temperature related internal stress states. The homogeneous warming and cooling of the structure hardly influences the measured deformation data because the extensometers themselves appear to experience similar temperature deformations as the cables, thus implicitly compensating temperature influences automatically.

It can therefore be concluded that the 5:00 am measurements represent a reliable and stable basis for the evaluation and interpretation of the deformation data. An explicit temperature compensation is not necessary for this data set. Over a time period of more than three years the system by now has provided high quality data. The scatter within the 5:00 am deformation data is below the intended overall precision of 0.1 mm so that the required basis for the reliable detection of potential wire fractures is given.

5.2 Verification of data quality

In spring of 2015 the pavement on the bridge superstructure was cut and later on replaced. The related change in cable forces could clearly be detected by the monitoring system (Figure 7). From finite element analysis of the structure the expected cable force variation could be determined and the related deformations along the effective gauge length could be calculated. Taking into account the stiffness contribution of the grout at small cable strains, the predicted cable deformations agreed with the measurements with an error of less than 5% for all eight cables.

For the long cable 1.1, shown in Figure 7.a, the theoretically estimated cable shortening due to cutting of the old pavement layer (thickness approx. 30 mm) was 0.09 mm which agrees well the observed measurement. The estimated elongation at re-application of the new pavement layer (≈ 45-50 mm) was 0.14 mm which also agrees well with the measurement. For the short cable 2.3 (Figure 7.b) the corresponding estimations were 0.12 mm and 0.19 mm, respectively, also agreeing reasonably well with the corresponding measurements. These results show that the monitoring system is not only running stable but also provides quantitatively high quality data.

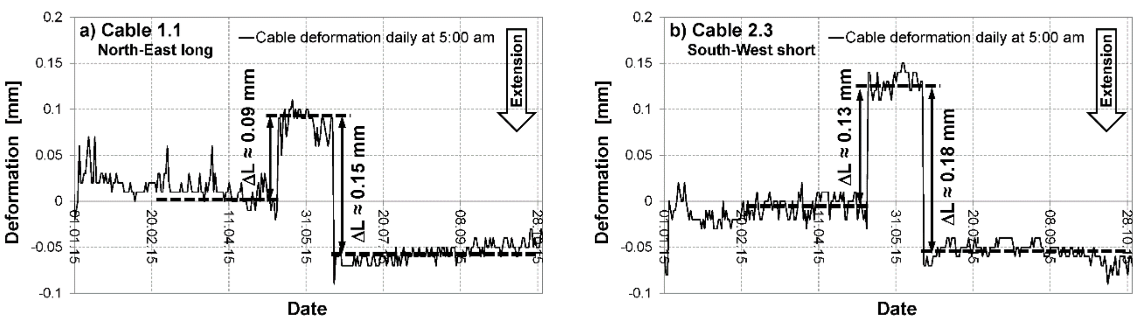

Figure 7. Deformations of (a) long and (b) short cable during cutting and re-application of pavement.

6 CONCLUSIONS

A novel concept for the permanent monitoring of stay cables has been developed. This approach is particularly suitable for older type cables consisting of post tensioning tendons running in grouted ducts, a system that in the past has exhibited deficiencies concerning the corrosion protection of the cables. A prerequisite for the successful application of this system is that the zone of potential wire fractures can be localized to a rather small region of each stay cable (typically the upper anchorage zone). This requires a detailed investigation of the cable condition in order to ensure that the rest of the cable can be considered as uncritical.

The monitoring system is based on the measurement of cable elongations along the potential fracture zone. It relies on the fact that in this zone the fracture of individual wires causes a stress increase in the remaining, unbroken wires. The correspondingly increased strains cause a lengthening of the cable in the fracture zone which can be detected by appropriate high quality extensometers. The details of their fixation require careful planning and execution.

The presented system has been successfully installed to a cable-stayed bridge in Switzerland and has now been running permanently for more than three years. The acquired measuring data are found to be stable and of high quality. The presented system can therefore be considered a both reliable and cost-efficient means to monitor the structural safety of the stay cables.

7 ACKNOWLEDGEMENTS

The detailing of the instrumentation and its fixation to the stay cables was developed and implemented in collaboration with Marcel Hubrig of Solexperts AG, Mönchaltorf, and Karl Lüpold of Stahlton AG, Frick. Their expertise and cooperative spirit was very valuable for the successful realization of the project. The project was lead and closely accompanied by Florian Mehnert of the Swiss Federal Roads Office (FEDRO). The support of all participating parties and their contribution is gratefully acknowledged.

8 REFERENCES

Alvarez, M., Matt, P., Meyer, L., and Vollmer, U. 2011, Schrägseile und externe Spannglieder für den Brückenbau, *ASTRA-Dokumentation 82015*, Bern: Bundesamt für Strassen.

Bülte, S., 2008, Zum Verbundverhalten von Spannstahl mit sofortigem Verbund unter Betriebs-beanspruchung, *Dissertation*, Lehrstuhl und Institut für Massivbau, RWTH Aachen.

Fricker, S., 2010, Schallemissionsanalyse zur Erfassung von Spanndrahtbrüchen bei Stahlbetonbrücken, *ibk report No. 329*, ETH Zürich.

Fédération internationale du béton (fib), 2013, *fib Model Code for Concrete Structures 2010*, Ernst & Sohn Verlag, Berlin.

Feldman, L.R., Bartlett, F.M., 2005, Bond Strength Variability in Pullout Specimens with Plain Reinforcement, *ACI Structural Journal*, Vol. 102, No. 6, pp. 860-867.

Feldman, L.R., Bartlett, F.M., 2007, Bond Stresses Along Plain Reinforcing Bars in Pullout Specimens, *ACI Structural Journal*, Vol. 104, No. 6, pp. 685-692.

Marti, P., Alvarez, M., Kaufmann, W., Sigrist, V., 1998, Tension Chord Model for Structural Concrete, *Structural Engineering International*, IABSE, Vol. 8, No. 4, pp. 287-298.

Martin, H., Noakowski, P., 1981, Verbundverhalten von Betonstählen, Untersuchung auf der Grundlage von Ausziehversuchen, in *DAfStb-Heft 319*, Deutscher Ausschuss für Stahlbeton, Berlin.

Rehm, G., 1961, Über die Grundlagen des Verbundes zwischen Stahl und Beton, *DAfStb-Heft 138*, Deutscher Ausschuss für Stahlbeton, Berlin.

Vollmer, U. 2007, Objekt 108, Birskopfsteg, Beurteilung und Dokumentation der Kabelzustände nach dem Öffnen der Hüllrohre, *Bericht 7355.501 (unpublished)*, Aegerter & Bosshardt AG, Basel.