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Laboratory study of fibre-optic strain sensor fixation for monitoring tunnel linings

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ABSTRACT: Construction of increasingly challenging urban infrastructure requires new approaches for monitoring solutions. This paper presents a study of strain sensor fixation systems for monitoring the deformation behaviour of existing tunnels. Achieving the highest possible sensitivity of the system while maintaining the necessary sensor protection is one of the major challenges. Another challenge is to achieve a high readout resolution and high spatial resolution at the same time. Two series of tests were performed to assess different types of magnets and protection systems for fixation. Short-term tests were performed to determine the largest applicable force for the magnet fixation and to assess the accuracy of the system. The long-term tests were carried out to investigate the creep, slippage under the magnet between neighbouring sections and temperature effects.

1 INTRODUCTION

The building of new urban infrastructure, in particular tunnels, is bringing major challenges since the routing often needs to be chosen below existing infrastructure. The construction of the new Crossrail line in central London is one example of such a project. Avoiding any disturbance to the structure of existing London Underground tunnels is of paramount importance in this project. Information about the deflection along the tunnel axis and squatting or egging in cross-section of the tunnel is thus very important and valuable for the responsible engineer on site.

The distributed nature of fibre-optic cables, where the cable itself is used as sensor and for transmission, makes it a predestined method for monitoring existing tunnels. A fast and reliable fixation of the sensor is one of the main difficulties in such a project. A promising method to fix the sensors to the flanges and the tunnel linings is the use of strong magnets. In addition, using an efficient method of fixation may decrease the time for installation per sensor compared to commercially available systems. This can be a crucial advantage in a tunnel where installation works needs to be done without interruption of the normal service. Distributed fibre-optic strain sensors were planned to be installed in an existing tube tunnel as part of a large field monitoring campaign of Imperial College London, ETH Zurich and Marmota Engineering AG.

This paper presents the results of preliminary laboratory tests that were performed in order to evaluate different fixation methods and the ability of the fibre-optic sensing system to detect strain changes in existing tunnels.

1.1 Motivation and challenges

Installation of fibre-optic cables on relatively stiff cast iron tunnel linings in a harsh environment brings several challenges.

First of all, the deformations due to the passing tunnel boring machine are small and the behaviour of the tunnel lining rings is very stiff. The expected strains in the segments and the joint deformations are thus very small and not much higher than the accuracy of currently available distributed fibre-optic readout units. This requires an installation with minimal slippage and a low noise level of the measured frequencies. In order to be able to measure joint openings between two flanges of the segments, the spatial resolution of the monitoring system needs to be in the sub-centimetre range.

The second issue is the tradeoff between the minimally required cable protection and the sensitivity of the whole monitoring system. On one hand, the less protection measures have to be applied, the less stiff is the cable. This results in higher system sensitivity and therefore enhances the ability of detecting small deformations. On the other hand, the sensor cable needs to be protected against fibre breakage due to sharp, uneven surfaces and against crushing due to the magnet being placed on top of the sensor. This issue can be eased by cleaning the surfaces before fixing the sensors which in turn expands the time needed for installation. Various fixations were tested with one or two magnets per fixation and different combinations of tape on the surface or on the magnet.

2 DISTRIBUTED FIBER-OPTIC SENSING

2.1 Technologies

Many different fibre-optic sensing technologies exist on the market which differ in terms of sensor length, spatial resolution, measurement accuracy and strain range. Stimulated Brillouin scattering technologies, such as Brillouin Optical Time Domain Analysis (BOTDA) (Niklès et. al (1996), Niklès (2007)) allow for measuring long distance cables with a spatial resolution of typically one meter. Rayleigh backscatter based technologies (e.g. Optical Frequency Domain Reflectometry, Kreger et. al (2006)) offer high spatial resolution in combination with shorter maximum sensor length.

Table 1: Specifications of selected distributed fibre-optic sensing technologies

Technology	Maximum Distance	Spatial resolution	Readout resolution (strain)
BOTDA	30 km	1 m	2 με
Rayleigh backscatter	70 m	1 mm	1 με

2.2 Strain sensing cables

Fibre-optic strain sensing cables, unlike optical fibres used in telecommunication, have to fulfil several requirements. The strain acting on the outer protection coating needs to be transferred down to the fibre without loss and the fibre needs to be protected against harsh installation and operational conditions. On the other hand, the cable design should be as sensitive as possible since it strongly influences the overall system measurement performance.

3 TESTING SETUP

The issues that need to be assessed for such a fixation system can basically be divided in two categories. The short-term test was designed to determine basic characteristics on one strained section and the fixation itself whereas the long-term test was used to investigate on several time dependent effects and the interaction between prestrained neighbouring sections.

3.1 Short-term behaviour testing

The short-term test was used to determine the largest force that can be applied on the fixation point before the magnet starts to move or the cable starts to slip under the magnet. This information is necessary to obtain the force limits and therefore the strain range which can be measured by the sensor system. In addition, the accuracy of the system can be obtained. The tests on the different fixations were carried out in a pullout device. The setup consists of a beam with a movable carriage connected to a step motor at one end (Figure 1). The sensor was installed using a rigid fixation at the immovable end and the magnet fixation system to be tested on the movable carriage. The displacement of the carriage and the force on the step motor can both be measured with high accuracy and resolution for reference. Short-term testing was conducted using Rayleigh backscatter technology to be able to see the effects around the fixation points.

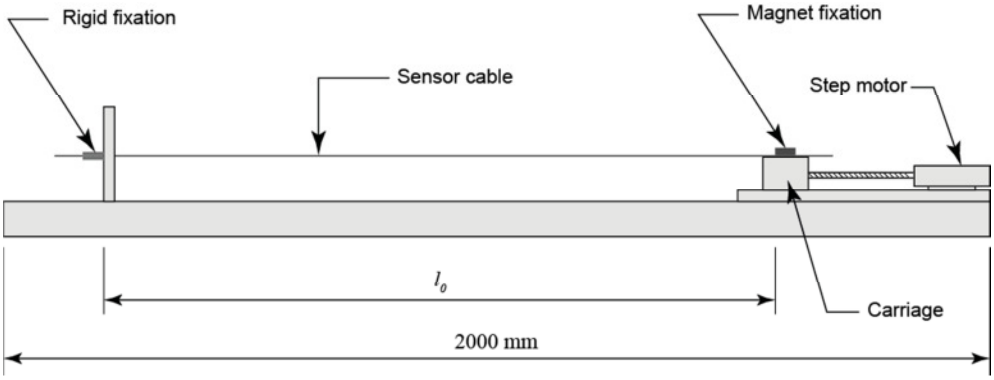

Figure 1: Schematic sketch of the pullout device

3.2 Long-term behaviour testing

The long-term test was used to identify and observe any effects that may happen to the fixation and the sensor system as a whole during the period in which it is installed. These effects involve for instance creeping, slippage under the magnet between neighbouring sections, temperature effects or flaking. A sensor cable, attached to a large-scale steel box, was used to investigate on these effects for different fixation systems. The cable was fixed to the box in meter or two metre

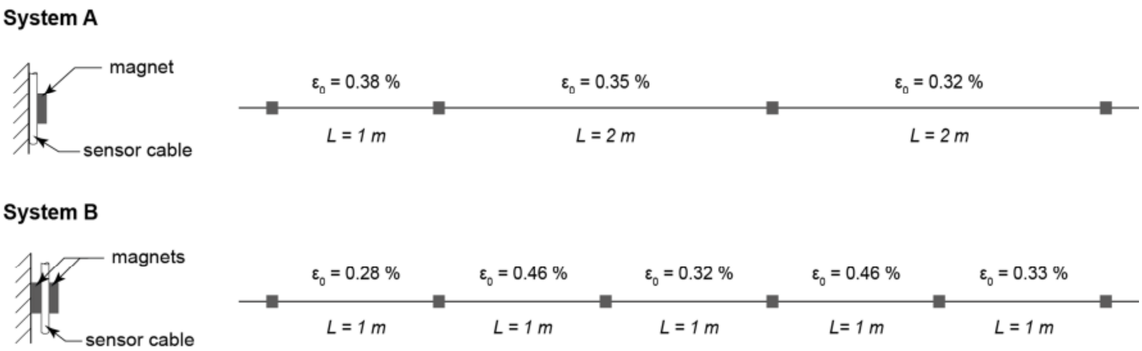

Figure 2: Schematic layout of the steel box test; left: cross-section; right: view

sections where every section had a different level of pretension ε_0 (Figure 2). Two different fixations were tested: System A was fixed with only one magnet whereas system B was fixed with two magnets on each side of the sensor cable (c.f. Figure 2). The trial lasted for several weeks and readings were taken automatically every four hours using a BOTDA interrogator. The spatial resolution was chosen to 1 meter and the sampling interval to 10 centimetres.

4 RESULTS

4.1 Short-term behaviour testing

4.1.1 System accuracy and maximal strain

The externally applied strain was increased up to 1% (10'000 με) and the strain in the cable was measured simultaneously (Figure 3, left). The experiment was conducted with and without tape as cable protection on the carriage. Tests without tape showed serious breakage of the cable coating and thus irregular strain distributions. Using tape on the carriage, however, gives enough protection for the cable and results in a linear behaviour with increasing strain (Figure 3, left).

4.1.2 Detectability of small strain changes

Small strain changes can be simulated with the highly precise step motor. A series of small strain increments was applied starting from reference strain levels of 0.6% and 1% (Figure 3, right).

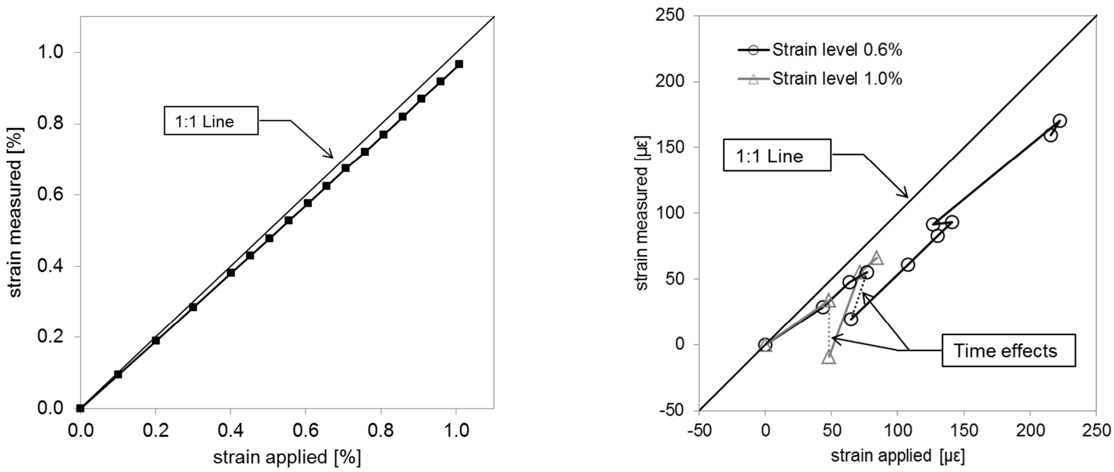

Figure 3: Applied strain vs. measured strain in pullout device with tape on the carriage

4.2 Long-term behaviour testing

The evolution of strains for both installed fixation systems, measured within the first 24 hours after installation, is shown in Figure 4. The sections are indicated with the dotted lines and the initial pretension of each section is stated in the upper part of the diagram.

It can be seen that there is slippage between the differently prestrained sections which results in changes of the strain level within each section. The strain level in more prestrained sections decreases whereas it increases in less strained sections. This effect is particularly strong at transitions to completely unstrained sections of the cable.

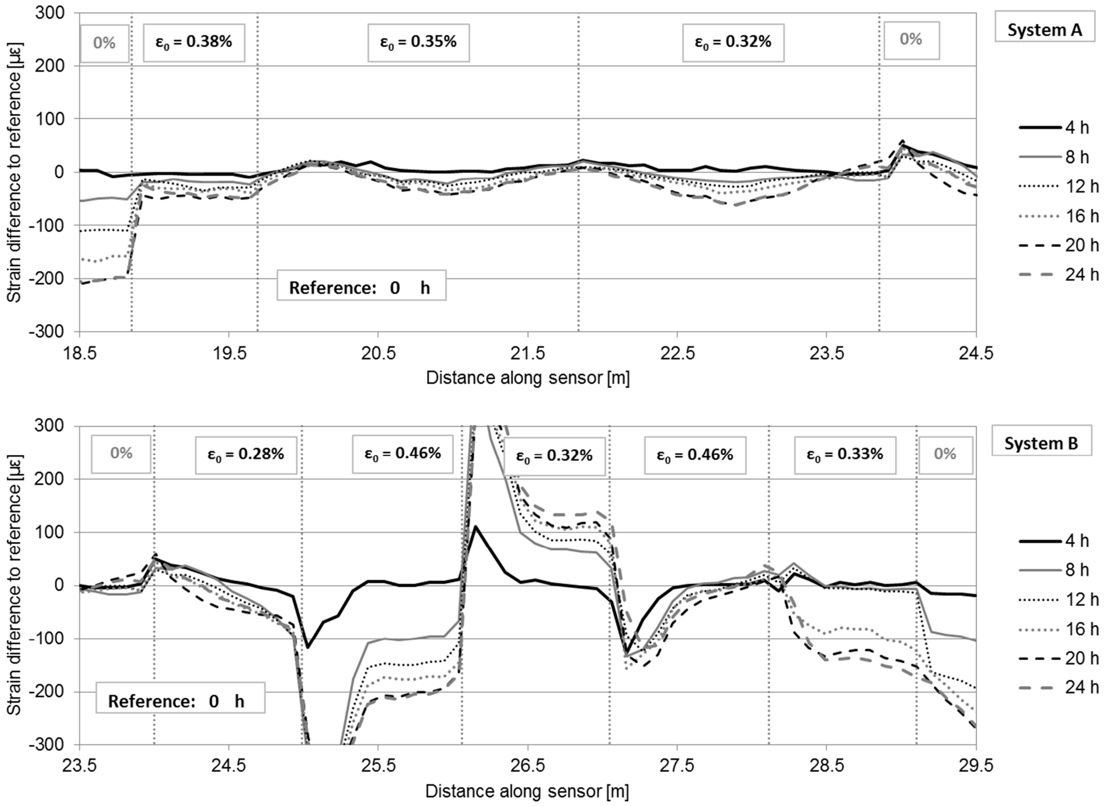

Figure 4: Strain evolution for both fixation systems within the first 24 hours (the dotted lines indicate the position of the magnets between each section; ε_0 indicates the initial pretension of each section)

The results after advanced test time show smaller strain changes within the sections (Figure 5). It can be seen that system A reaches a state of equilibrium. Significant strain changes only occur at transitions to unstrained sections whereas the strain in sections with strained neighbouring sections stays constant. The strains in system B still vary considerably and strain is still transferred from more to less prestrained sections.

5 DISCUSSION OF TEST RESULTS

5.1 *System accuracy and maximal strain*

The maximal strain that can be detained by the magnet is of high importance for the selected fixation system. A first test, conducted using the pullout device, shows high strain levels (1%) that can be achieved without having major slippage between the magnet and the cable. The results show a constant ratio between applied and measured strain and the absolute system error is lower than 5%. Possible reasons for the lower measured strain might be the slackness of the step motor or the influence of cable protection measures such as the tape on the magnets.

5.2 *Detectability of small strain changes*

The test in the pullout device showed that strain changes of a few tens of microstrains can be detected and quantified. The results show a high accuracy and a linear behaviour for most positive strain increments. The reason for lower accuracy may be the slackness or the inertness of the system, especially for the first applied increment (Figure 3, right). The accuracy of

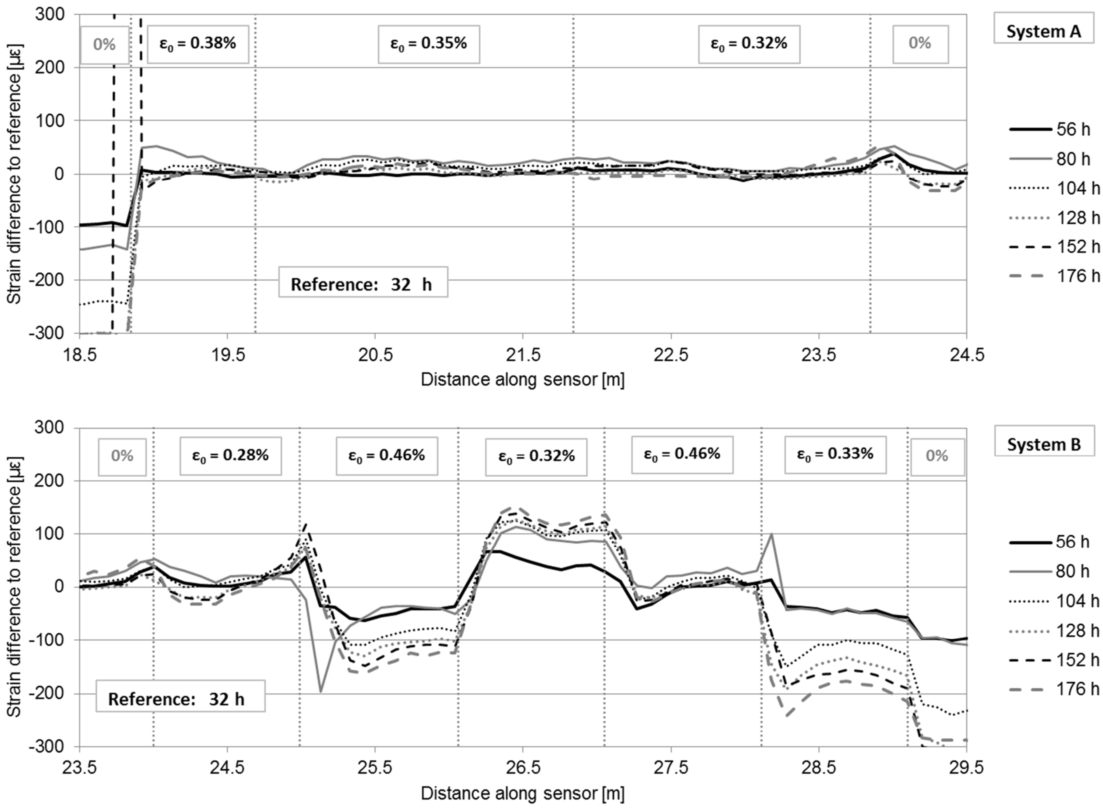

Figure 5: Strain changes for both fixation systems between 32 and 176 hours after installation (the dotted lines indicate the position of the magnets between each section; ε_0 indicates the initial pretension of each section)

negative strain increments (or generally in reverse direction) is not as high as for positive strains for the same reasons as explained above.

5.3 *Slippage behaviour and interchange between neighbouring sections*

Slippage mainly occurs at interfaces with large strain differences (e.g. > 0.1%), which is in particular at transition to completely unstrained cable sections. The relatively low threshold for the strain difference compared to the 1% in the short-term test may be explained by creeping effects due to higher protection measures of the fixation system in the long-term test. Large differences in strain levels thus have to be avoided in a real tunnel installation, especially at the end of the distance to be monitored.

5.4 *Evaluation of different fixation methods*

The long-term test was also used for testing different cable fixation methods on a steel surface. System A uses one magnet combined with tape whereas system B consists of two magnets for fixation of the cable (Figure 2).

As stated in the previous section, system A reaches a steady equilibrium state after certain time whereas the strain levels in system B keep changing even after advanced time. It is obvious that system B is not suitable for real measurement since real strain changes cannot be distinguished from random strain changes. The reason for the noisy strain changes might be crushing of the fibre which is clamped between the two magnets in the fixation point. This would also explain the very high and irregular strain changes right at the fixation point.

The strain difference between two neighbouring sections and the fixation method apparently have the largest influence on the stability of the strain levels. The length of the prestrained section however has a minor influence.

6 APPLICATION EXAMPLE

6.1 Test setup and programme

A first application test of the fixation system A was conducted on a large-scale ring of lining segments (Figure 6). The aim of the test was to assess whether the tested fixation system in combination with a high resolution readout unit is able to detect relatively high strain changes over a short length. The sensor cable was fixed on the flange on each side of radial joints (Figure 6, left) and inside a lining segment (Figure 6, right). Across the crest segment at the top of the ring, the sensor cable was strained as well to see the influence of differently prestrained, neighbouring sections.

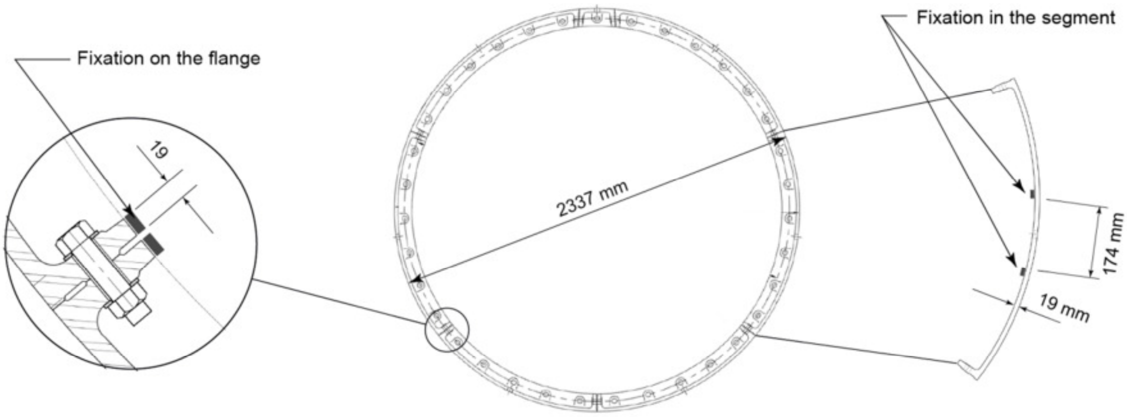

Figure 6: Cross-section of model ring with details of the attached FO cables (Courtesy of Imperial College, London)

In initial stage of the test, the ring was standing in upright position, only loaded by its self-weight. In three subsequent stages, the ring was lifted by crane at its crest which caused lateral joints to open and joints at the bottom and top to close. This process can be described as a transition from a squatted cross-section to an egged cross-section. The strains were measured using a Rayleigh backscatter readout unit with a spatial resolution in the sub-centimetre range.

6.2 Results

The joint deformations and the very small strain changes within the lining segment are clearly detectable using the described fixation system (Figure 7). The dimensions of the magnets attaching the cable are marked by dotted lines in Figure 7. The spatial resolution turns out to be high enough to localise the prestrained section within the segment with an accuracy in length of 1 millimetre. The location of the closing joint can also be determined even though the cable is slipping under the magnet. The prestrained section in the crest, next to a joint, can be detected as well and clearly distinguished from the strains caused by the closing joint (Figure 7, left).

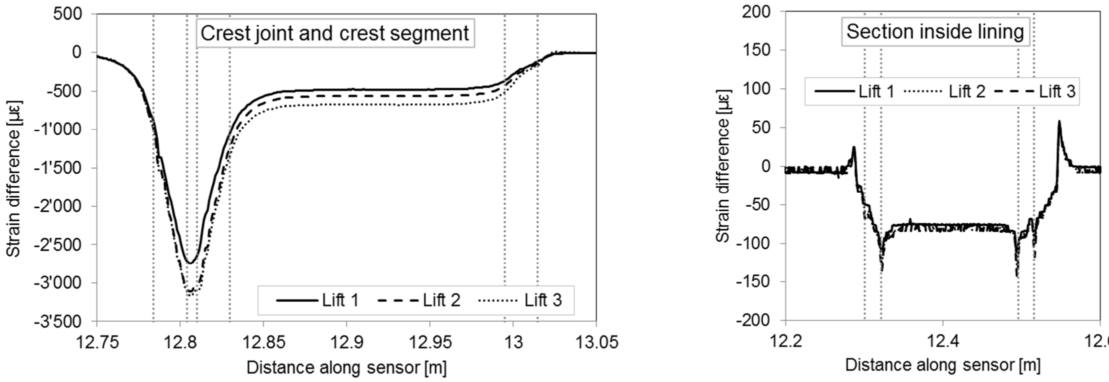

Figure 7: a) Joint next to the prestrained crest section b) prestrained section within a lining segment

7 CONCLUSIONS

The use of magnets for attaching sensor cables to iron tunnel linings was found to be an appropriate method. The choice of the right number and strength of the magnet as well as the adequate cable protection (e.g., tape), is, however, an equally important factor. One magnet on each side, for example, makes the fibre crush and disturbs the measurements significantly while too little protection by tape destroys the coating. Small strain changes, as they can occur in tunnels, are measurable with a system accuracy of a few tens of microstrains. The slippage under a magnet in a fixation point basically vanishes as long as the difference in strain level of the adjacent sections is kept reasonably low (< 0.1 %).

The use of a readout unit with high spatial resolution also allows for detecting strain changes in a very short section as can be seen in the application example. This highly precise method with high spatial resolution can provide project engineers on the site with very valuable real-time information. Availability of a quickly installable fixation system is highly important since a lot of monitoring is carried out without interruption of the service and not much time is available for installation. The whole system seems to be promising for monitoring deformations in existing tunnels. The proposed system was recently applied in a large-scale monitoring of a London Underground tunnel during the passing of a Crossrail TBM nearby.

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