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ANALYSIS OF STRUCTURAL PERFORMANCE USING FIBRE OPTIC MEASUREMENT TECHNOLOGY

Abstract: The paper describes the application of optical fibres for the structural monitoring which may be undertaken to establish the long-term of structures, components of construction and building materials. Condition monitoring is also used in repair and strengthening works. Examples of determination of strain, temperature and moisture content have been given. Two interesting examples of measurement using fibre optic technology were the monitoring of an actual bridge in Norway, subjected to controlled loading conditions, and tunnel deformations during the construction of a subway system in Japan. The presented results shows that the monitoring process using optical fibres has a great potential.

Key words: fibre optic technology, structural monitoring, temperature monitoring, moisture absorption, tunnelling.

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АНАЛИЗ ХАРАКТЕРИСТИК КОНСТРУКЦИЙ С ИСПОЛЬЗОВАНИЕМ ОПТО-ВОЛОКОННЫХ ИЗМЕРИТЕЛЬНЫХ ТЕХНОЛОГИЙ

Аннотация: В статье рассмотрено применение оптических волокон для мониторинга конструкций, который может быть предпринят для установления долговременности конструкций, компонентов строительных и строительных материалов. Мониторинг состояния также используется в ремонтных и укрепительных работах. Приведены примеры определения деформации, температуры и влажности. Двумя интересными примерами измерений с использованием волоконно-оптической технологии являются мониторинг фактического моста в Норвегии, подвергающегося контролируемым условиям нагрузки, и деформация туннеля во время строительства системы метро в Японии. Представленные результаты показывают, что процесс мониторинга с использованием оптических волокон имеет большой потенциал.

Ключевые слова: оптоволоконные технологии, мониторинг конструкций, контроль температуры, водопоглощение, прокладка тоннелей.

1. Introduction

This paper is devoted to the results of developing optical fibre monitoring systems for strain, temperature and moisture measurement. These systems have been deployed in steel, concrete and composite steel-concrete and polymer composite structures. Available strain sensors, which rely on electrical instrumentation, require a large amount of electrical connections, can be difficult to distribute over large distances and to embed during construction. The distributed, multiplexed optical fibre sensor systems developed will provide information regarding stress relief, shrinkage, creep, dead loading, post tensioning and cracks and corrosion. It is possible to monitor the static and dynamic loading that is essential in setting controlled maintenance procedures and scheduling and for structural design assessment. This provides a means to determine the service quality and safety, during and after construction, throughout the structures lifetime and following unusual phenomena such as earthquakes

2. Technology of Optical Fibre Instrumentation

2.1 Monitoring of Strain

The Bragg grating structure is written as a periodic variation in the refractive index of a photosensitive fibre providing a strain and temperature dependent optical filter. The grating effectively acts as a wavelength specific mirror whilst allowing all other light to pass almost perfectly in order to interrogate further gratings if used in a multiplexed system, Figure 1. The grating forms the basis of optical strain measurements, which can be monitored by measuring the changes in the wavelength spectrum of the reflected optical signal. It allows an absolute measurement that is independent of potential intensity fluctuations caused by light source variation, fibre bending loss or connector attenuation. It is simple and encapsulates all the benefits of optical fibre technology. This is a major advantage of Bragg grating sensors for long term monitoring in large engineering structures where the service lifetime of the structure is considerable. Bragg gratings are passive optical sensing devices, immune to electromagnetic interference. The gratings are etched directly into the fibre, are unobtrusive and very small, Figure 2, allowing easy sensor embedment for smart structure applications. Several gratings can be written in series along a single fibre at different wavelengths for quasi-distributed sensing, a major advantage of the use of this approach.

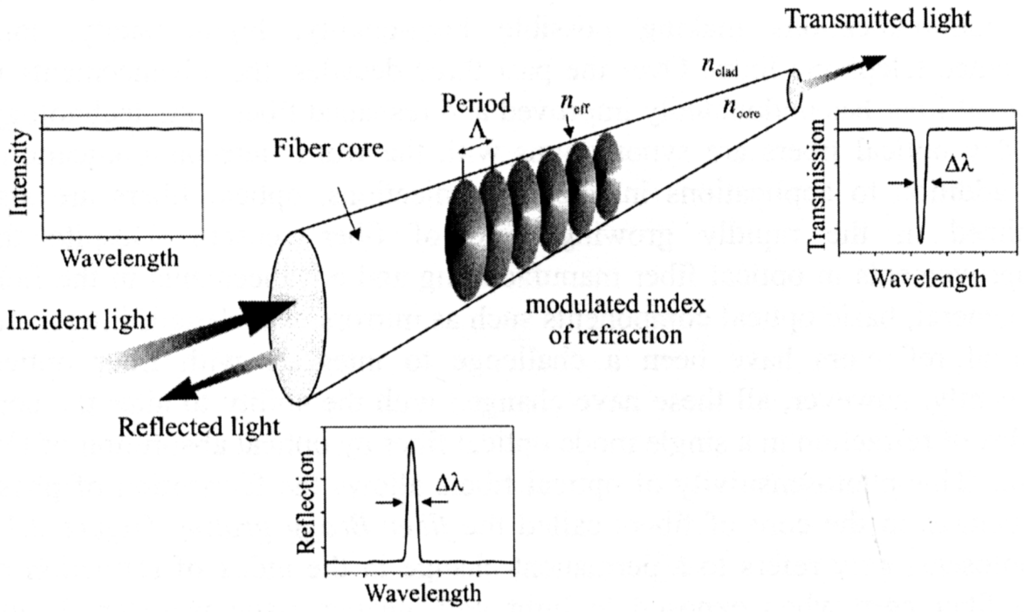


Figure 1. Representation of operation of FBG based strain instrumentation

Figure 2. Strain gauges and optical fibre sensors on failed concrete specimens

2.2 Monitoring of Temperature

A fibre-based sensor system for temperature monitoring using a technique complementary to the Bragg grating based system for strain monitoring has been developed. This allows the measurement of temperature and would provide a mechanism to compensate changes in the strain measurements within a structure caused by changes in temperature. The method proposed uses small temperature-sensitive elements of doped fluorescent fibre, the fluorescence decay time of which can be monitored as a function of temperature. This technique is sensitive over the whole range of temperatures to be measured in a structure (-20 to +350^{o}C) and utilises the same wavelengths as the strain measurement system, to simplify the optical system used. Signal processing using readily available electronic components, provides a resolution of ±2 ^{o}C with the probe in-situ. Figure 3 shows the optical fibre probe.

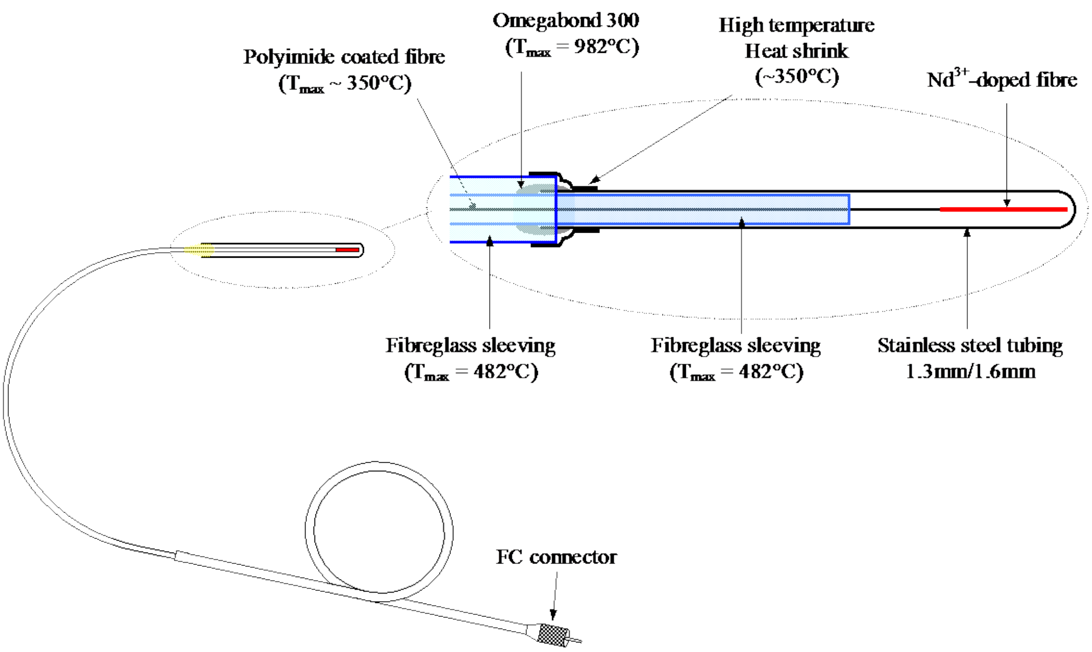


Figure 3. Design of optical fibre temperature probe

3. Examples of Applications

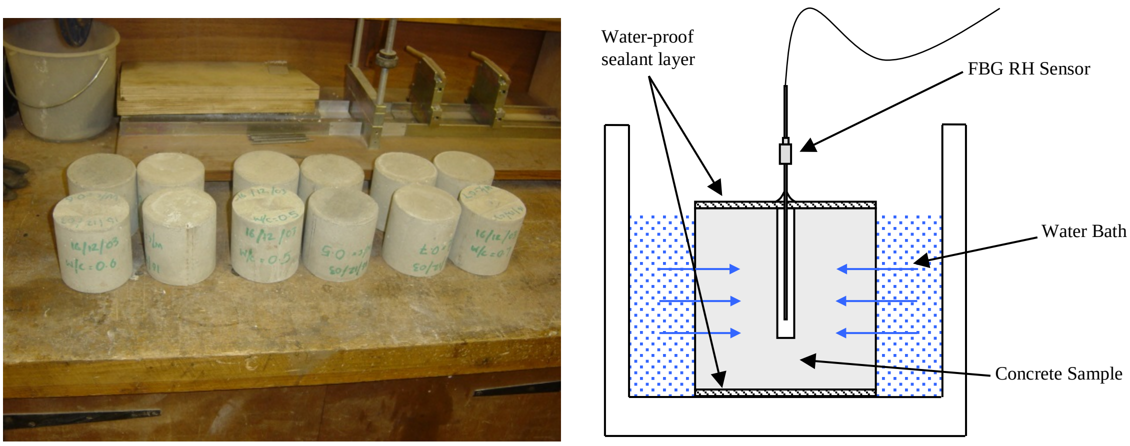
Some examples of developed and proven optical fibre sensors for civil engineering structures are given.

3.1. Moisture Absorption in Concrete

A humidity sensor has been developed and used for the measurement of moisture absorption in concrete. The sensor was fabricated using a fibre Bragg grating coated with a moisture sensitive polymer. To investigate the performance of the sensor to detect moisture ingress in concrete, it was embedded into concrete samples of different water to cement ratios, which were then immersed in water. A direct indication of the humidity level within a sample is given by the shift of the Bragg wavelength caused by the expansion of the humidity-sensitive material coated on the fibre. Strain is induced in the grating through the swelling of the polymer coating.

The influence of humidity and humidity detection polymer-coated FBG's has been discussed by Giacarri et al (2001) and Yeo et al (2005). Different chemical coatings will have different responses to humidity change. Polyimide was used as the coating material as a linear response is preferred. Samples of concrete with a humidity sensor embedded were placed in water and the rate of absorption was measured from the rate of the humidity change, Yeo et al (2006).

The durability of concrete is its ability to withstand the process of deterioration to which it is exposed. This may be due to chemical attack and the repeated "freeze thaw effects" of water absorbed in the concrete. Tests for the measurement of permeability have not been standardised and values quoted from different sources may not be comparable.



a *b*

Figure 4. *a* – concrete samples of different water/cement ratio,
b – A concrete sample with a RH sensor in the water bath

Cylindrical concrete specimens were made with a diameter of 100 mm and depth 100 mm , Figure 4 a. They were cast with a 4 mm diameter hole at the centre, with a depth of 80 mm into which the sensor could be placed. Three different mixes were made, with water/cement (w/c) ratios of 0.5, 0.6 and 0.7 respectively. The 28 day compressive strengths were obtained from concrete cubes. For each test, a sample was set up with the probe placed in the centre of the concrete cylinder, Figure 4 b. A typical result is shown in Figure 5 a,b,c,d. It can be seen that the ingress of water into concrete specimens can be measured using the method.

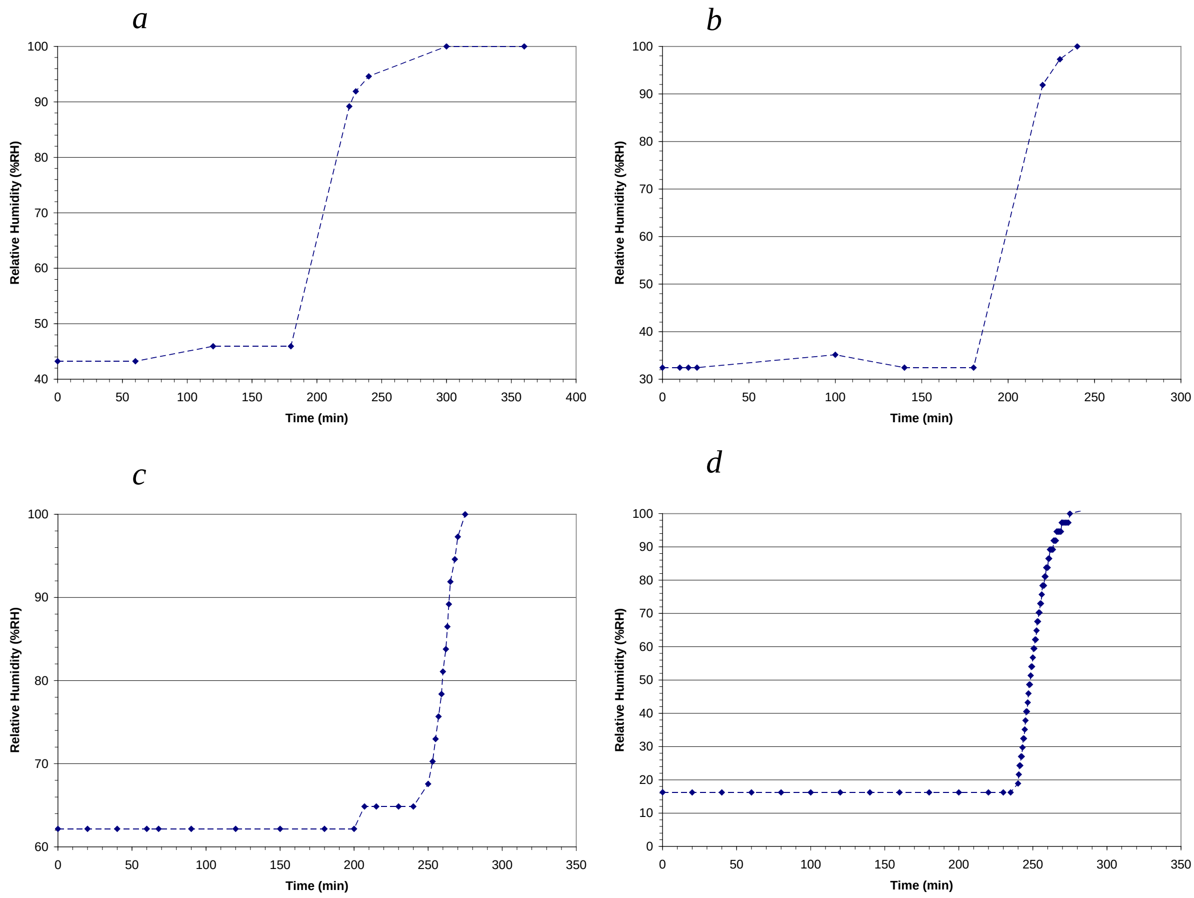


Figure 5. Result for samples: *a* – sample with w/c ratio of 0.6, oven dried at 80°C for 24 hours; *b* – sample with w/c ratio of 0.7, oven dried at 80°C for 24 hours; *c* – sample with w/c ratio of 0.5, oven dried at 95°C for 48 hours; *d* – sample with w/c ratio of 0.7, Oven dried at 95°C for 48 hours

3.2 Strain and Temperature Measurements for Concrete Beams

A series of tests for reinforced concrete beams was used to evaluate the durability of optical fibre sensors exposed to high temperature. The dimensions of the beams were; length 850 mm, height 85 mm, width 60 mm .The work was carried out using the optical fibre sensor as well as FBG sensors for strain and temperature evaluation. Measurements using electrical resistance gauges and thermocouples were also made. The beam was subjected to a 10 kN load (40 % of static capacity) at ambient temperature, during which the temperature of the beam was monitored using a K type thermocouple and an optical fibre temperature probe. The beam temperature was increased in increments of 100 degrees to a maximum of 300 degrees centigrade.

FBG sensors were also used to measure strain and to compensate for temperature variations within concrete beams subjected to structural and thermal loads. Two FBG sensors were installed in the concrete beam with one attached to the steel reinforcement and the other inserted into a glass capillary in order that it would only be subjected to thermal variations and was located adjacent to the first sensor. The compensated strains measured by the FBG sensor on the reinforcement compared favourably with the electrical resistance gauges, Figure 6.

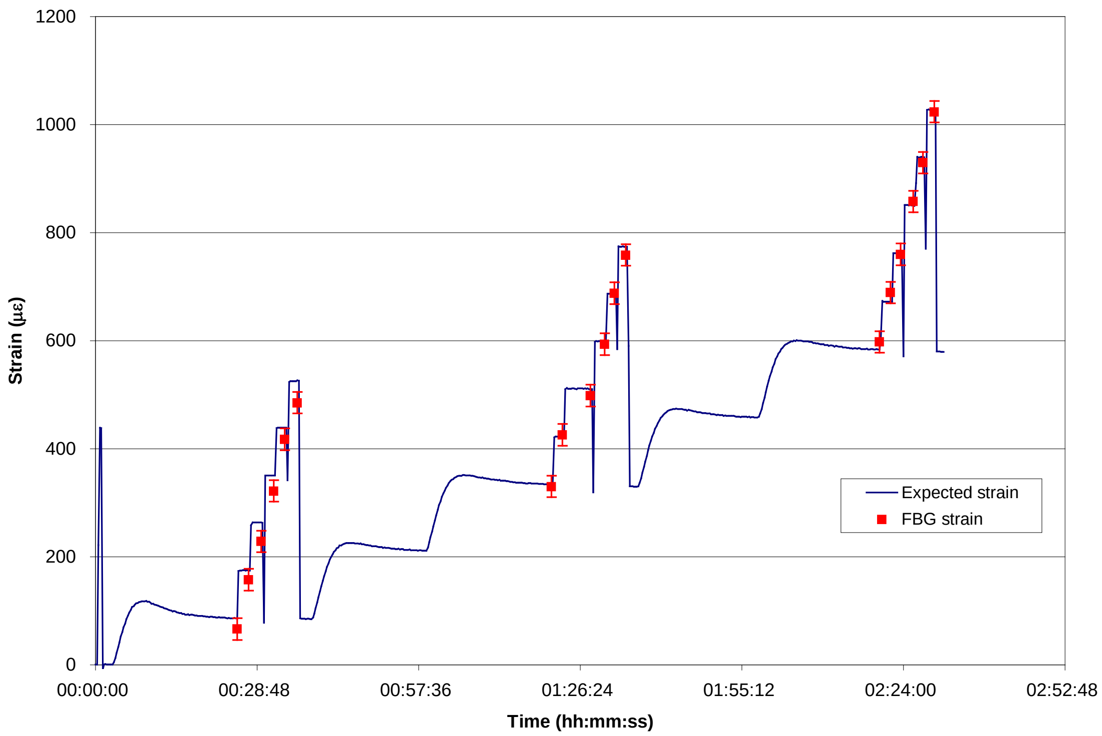


Figure 6. Comparison of temperature compensated FBG sensors to strain gauge measurements

3.3 Bridge Monitoring

The Mjosundet Bridge is located in Norway. It is a five span continuous composite bridge, Figure 7. There are two end spans of 41m, two intermediate spans of 82m and a centre span of 100m giving a total length of 346m. The deck is made of concrete, fixed with shear connectors to the top flanges of the steel box, Figure 8.

A model of the bridge was used to test and implement the hardware and software for data acquisition. A comparison with existing strain measuring techniques and optical fibre monitoring techniques was undertaken. Thus two systems were assembled that would run as a single unit during the field trial tests. The first system was an electrical (ERSG) system used to monitor the strain gauges that were attached to the structure. The second system was the optical fibre based fibre Bragg grating (FBG) system, which had been specifically developed to be capable of monitoring up to 100 sensors. In order to provide further information for the strain measurements, a separate finite element study was conducted.

Figure 7. Mjosundet bridge used for the field trials

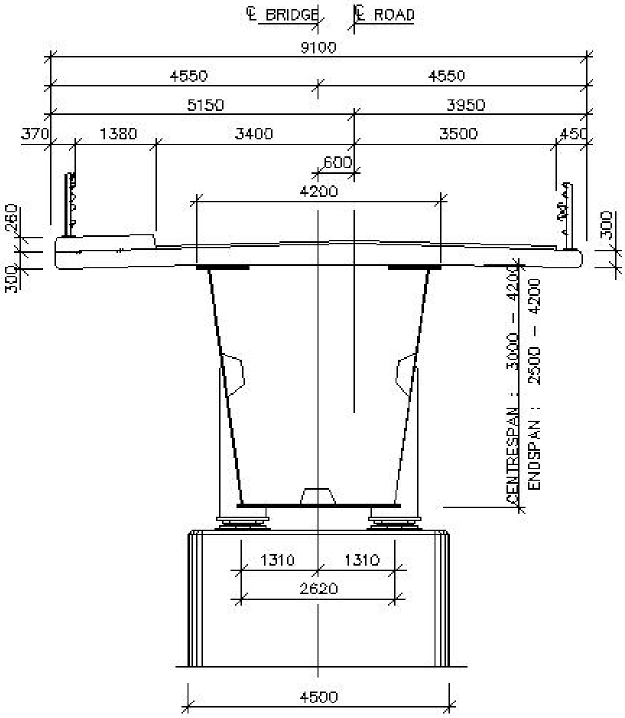


Figure 8. Typical cross-section of bridge

The bridge was instrumented on two cross sections and the placement of the instrumentation was determined by a finite element analysis in order to provide guidance to the most effective positions. These positions were determined as having the highest strains within the steel structure, which would then be used within a fatigue analysis.

Each of the individual field trials consisted of a number of static and dynamic tests where the structure was subjected to loads from a number of parked or moving vehicles, respectively. The static tests consisted of three loading states where the structure was subjected to maximum sagging and hogging moments and maximum shear forces up to the design load levels. A series of discrete load and no-load events allowed data to be recorded continuously for the test and easily processed afterwards. During the dynamic tests, the vehicle was driven across the structure at a steady velocity. A number of these tests also involved the vehicle being driven over a plank in order to induce shock vibrations and, hence record data during natural frequency oscillations.

Figure 9 shows a comparison of data acquired from both measurement systems with that obtained from the finite element analysis. A comparison is made for one load case and each figure represents the longitudinally aligned sensors from one of the monitored cross sections. The figure shows the bending of the structure with the neutral axis located approximately 2.5m to 2.75m above the lower flange of the structure. The data from the two measuring systems agree well with each other, which are slightly underestimated by the finite element analysis. However, since the gradients of these lines are equivalent it has been assumed that this difference is due to an axial force in the structure during the load test caused by fixture of the deck between the columns.

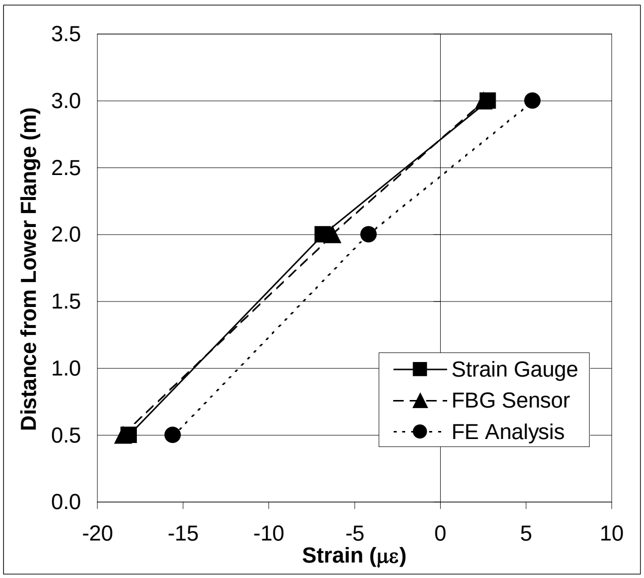
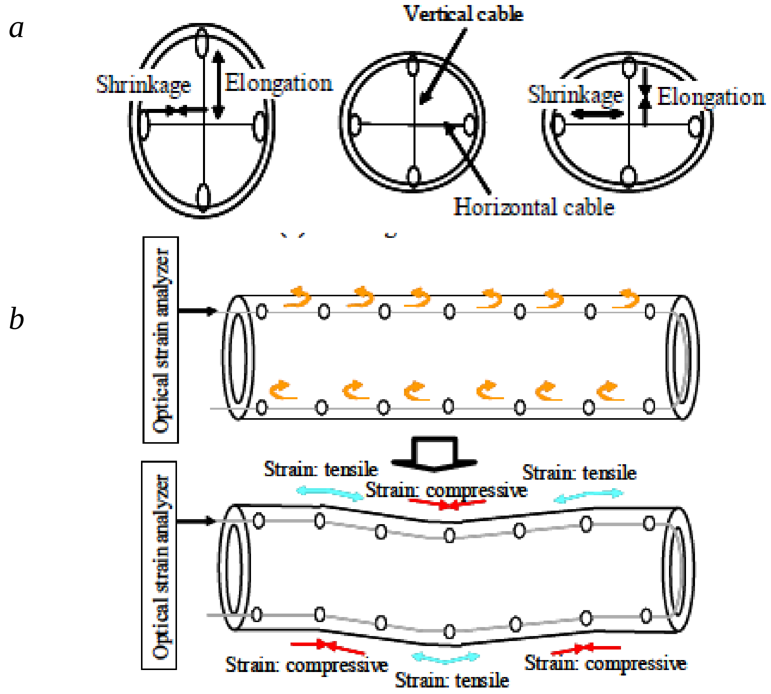


Figure 9. Comparison of data at support location (high shear loads)



Figur 10. Installation of the optic fibre in the tunnel: *a* – covergents measurements; *b* – settlement along tunnel axis

4. Monitoring during Tunnelling

In a recent application, Horichi et al (2010) optical fibre sensors were installed in an existing tunnel in Tokyo to determine the changes in cross section and tunnel displacements during the advance of the Joban New Line tunnel boring machine, Figure 10 a,b.

Figure 11 shows values of settlement along the axis of the NTT tunnel, obtained through fibre optic measurement with accuracy of 100 µ. Settlements curves slope for a distance about 20 m on both sides of the location of the cable tunnel cross section at the centre of intersection with the shield-driven railway tunnel, are in close agreement with the theory of a beam on an elastic foundation.

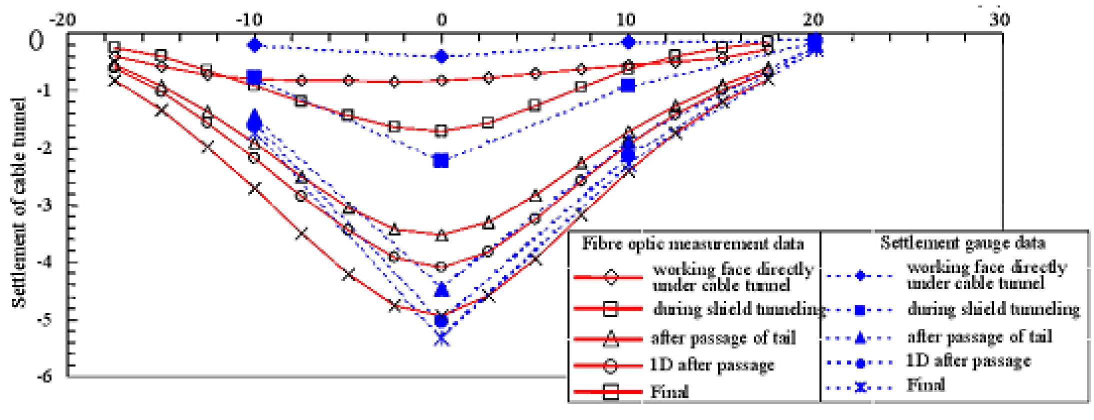


Figure 11. Settlement of the cable tunnel

The optical fibre measurement proved to be reliable not only for actual monitoring, but for the verification of appropriate geotechnical models for the prediction of soil stress and pore water pressures.

5. Conclusions

FBG and fluorescence-decay optical fibre based sensor systems have been developed and assessed for the monitoring the structural integrity of civil engineering structures. The development of suitable surface and embedment techniques and protection systems for using optical fibre sensors in the field has been developed and validated using concrete cylinder and reinforced concrete beam tests. The sensors have been subjected to static, fatigue and thermal loading within reinforced concrete test structures and have shown excellent results throughout. The sensors attached directly to structures have correctly measured strain and temperature to ±1 microstrain and ±2° C, respectively and dynamic strains of approximately 3000 microstrain whilst monitoring fatigue loading of reinforced concrete beams. The sensors have also monitored the stress-strain response of concrete specimens subjected to various environmental conditions. The results achieved indicate that the optical fibre probes are robust and can withstand large and sudden changes in the load applied to the test structure.

A particular interesting development has been the application to the measurement of moisture ingress in to concrete. This is the mechanism of chloride attack and a probe has been developed to develop humidity change in concrete.

The successful application of FBG sensors for monitoring the short and long term loading of bridge structures has been conducted with continuous data being recorded for a period of 17 months.

Monitoring during the construction of a subway tunnel in Tokyo is a further example of the versatility of optical fibre measurements in Civil Engineering.

The use of optical fibre based technologies within civil engineering has been proven to be of use for further investigations. Sensors are currently being developed to measure the ingress of moisture and chlorides into concrete structures that can ultimately lead to an increased understanding of the behaviour of the materials involved and their resistance to chemical attack.

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