USE OF OPTICAL FIBRE TECHNOLOGY TO MEASURE STRUCTURAL PERFORMANCE

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Abstract: Structural monitoring using optical fibre technology may be undertaken to establish the long-term behaviour of structures, components and materials of construction. Condition monitoring may be used in repair and strengthening schedules. The establishment of material durability is also part of the monitoring process. The paper describes the application and development of the use of optical fibres to monitor structures. Examples have been given in which, strain, temperature and moisture content have been determined for structural elements and materials of construction. Of particular interest is the use of an optical fibre system to determine the performance of an actual bridge in Norway, subjected to controlled loading conditions. A further example was the monitoring of tunnel deformations during the construction of a subway system in Tokyo. The results, which have been presented, demonstrate the potential to monitor structures using optical fibres.

1. Introduction.

This paper presents the results of research to develop 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 that is time consuming to install, 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 structural degradation manifested by the appearance of 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. Optical Fibre Instrumentation Technology.

2.1. Strain Measurement.

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.

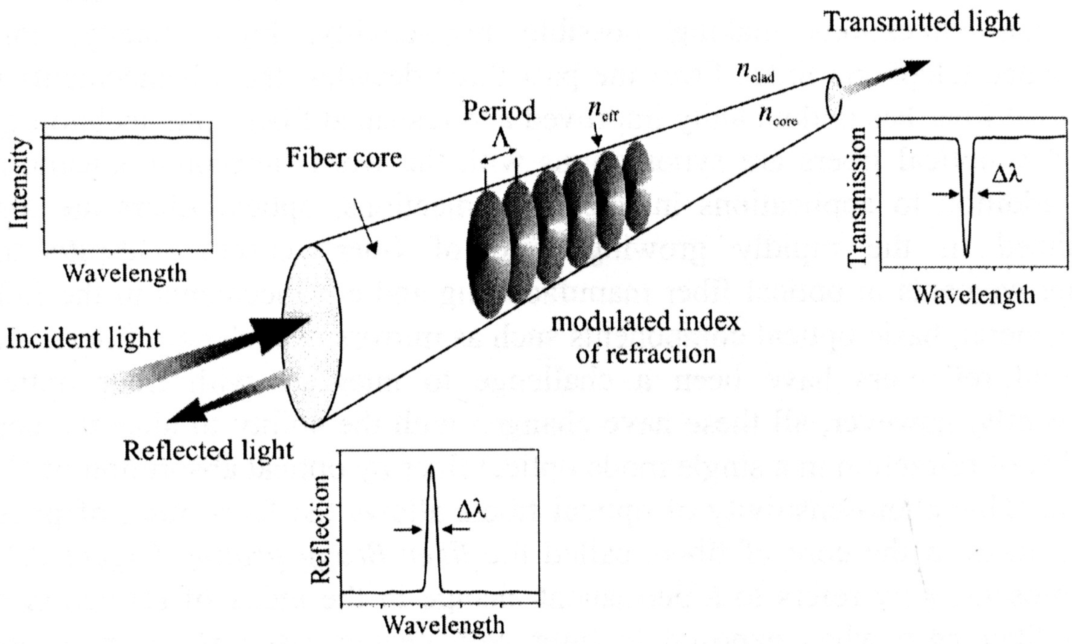


Figure 1. Schematic representation of operation of FBG based strain instrumentation.

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

2.2. Temperature Measurement.

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 +350ºC) 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 ºC with the probe in-situ. Figure 3 shows the optical fibre probe.

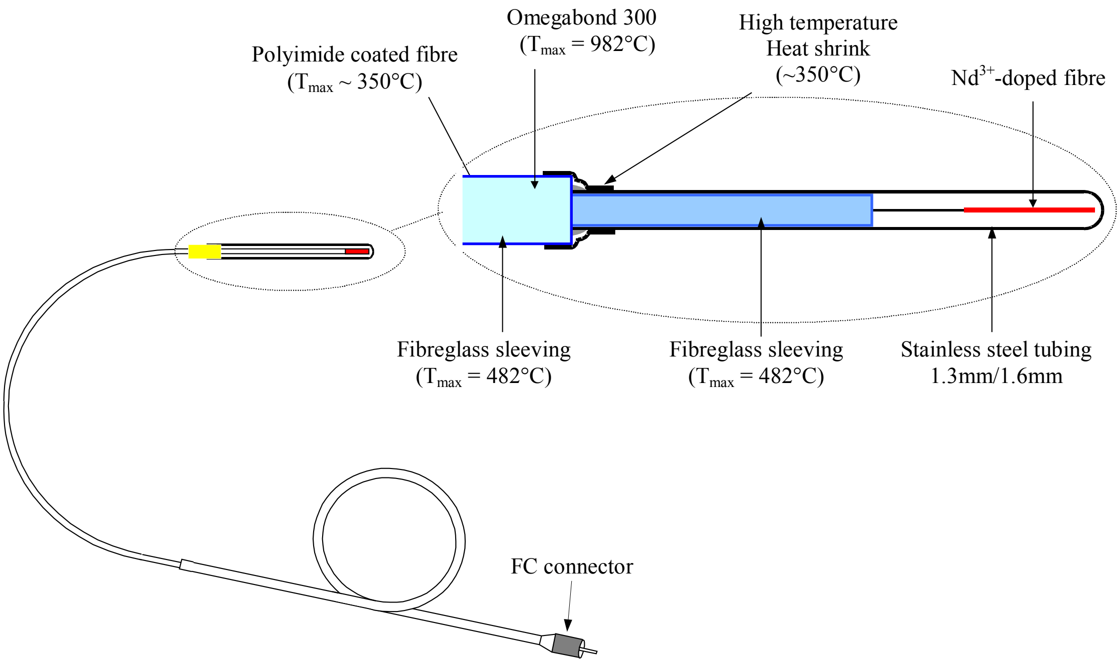


Figure 3. Design of optical fibre temperature probe for temperatures up to 350°C, and installed in a reinforcement cage.

3. Applications.

The application of optical fibre sensors for civil engineering structures has been developed and proven. Some examples of this work are given.

3.1. Strain and Temperature Measurements for Concrete Beams.

A series of tests using 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 a 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.

3.2 Durability of Concrete Cylinders

A programme of work to assess the effect of damage development in dry and pre-conditioned concrete cylinders and cubes as a function of applied load and curing environment was undertaken.

The specimens were cured under four different conditions and then loaded to a series of pre-defined levels and then unloaded, sectioned, and inspected. The behaviour as a function of load and environment was obtained from the output from the FBG sensors attached to the cylinders and from ultrasonic pulse velocities, which is a common method of measuring relative, in-situ degradation of concrete structures. The results showed significant difference in the stress-strain behaviour between the concrete cylinders cured under the different environmental conditions. The strength of the concrete under the different curing regimes is related to the amount of moisture available for concrete hydration. The specimens cured under control conditions achieved design 28 day strengths of $40Nmm^{-2}$ with the higher humidity levels causing increased strength. The samples cured in air had reduced strength. The stress-strain response of specimens measured using optical fibre sensors, which was detectable at very low levels of stress. The measurement of changes in ultrasonic pulse velocities proved to be less accurate.

3.3. Fatigue Tests on Concrete Beams.

Reinforced concrete beams were subjected to dynamic fatigue loading at various load levels to determine the performance of sensors at low loading (up to 10^6 cycles), intermediate and high loading (<1000 cycles). A single optical fibre sensor and two electrical resistance strain gauges were used for monitoring the compression strains at the centre of the test specimens, Figure 2. The design of the beams ensured failure occurred by concrete compression at mid span. For a beam loaded at low levels, the strain range increased up to $6.5x10^5$ cycles, after which it remained steady and the test was stopped after 10^6 cycles. Specimens that were highly loaded showed rapid degradation of the beam by the continuously increasing strain range and increasing residual strain within the beam.

Figure 4 shows the number of cycles to failure from nine concrete beam tests, which have been subjected to various load ranges. Two of the specimens did not actually fail and are highlighted by the dotted lines indicating when the failure might be expected to occur. The results from this work have enabled a fatigue curve to be generated for concrete in compression.

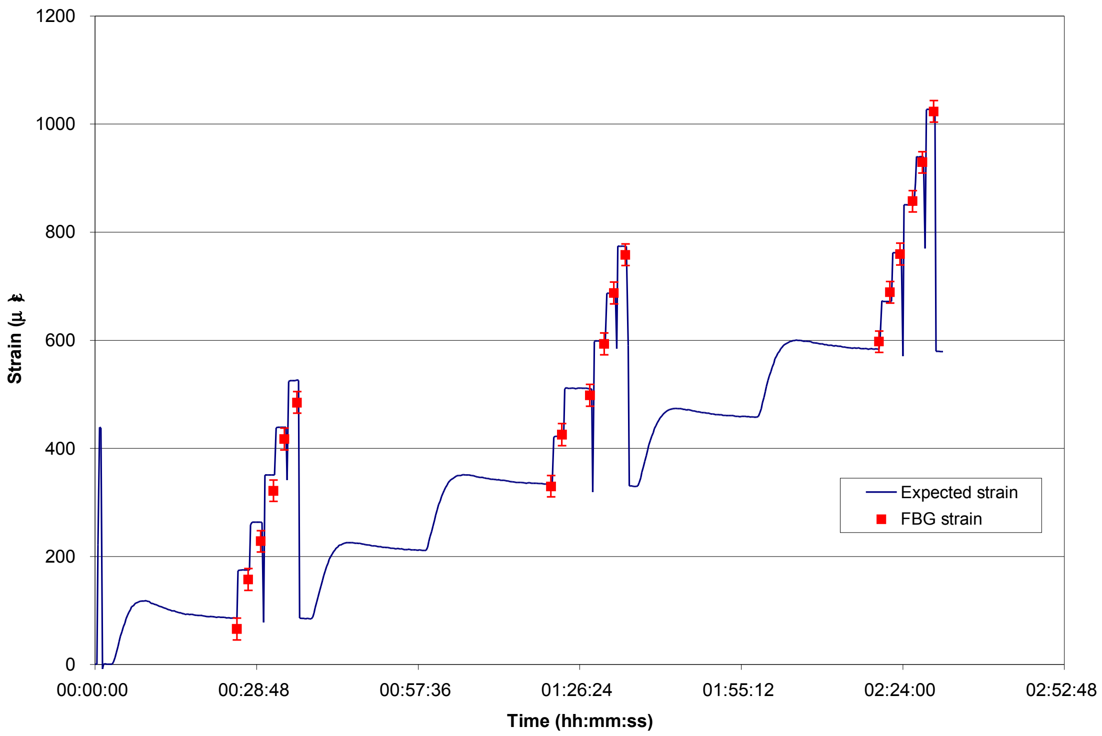


Figure 4. Comparison of temperature compensated FBG sensors to strain gauge measurements.

3.4. The Measurement of 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.

Cylindrical concrete specimens were made with a diameter of 100 mm and depth 100 mm , Figure 5a. 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 5b.A typical result is shown in Figure 6. It can be seen that the ingress of water into concrete specimens can be measured using the method.

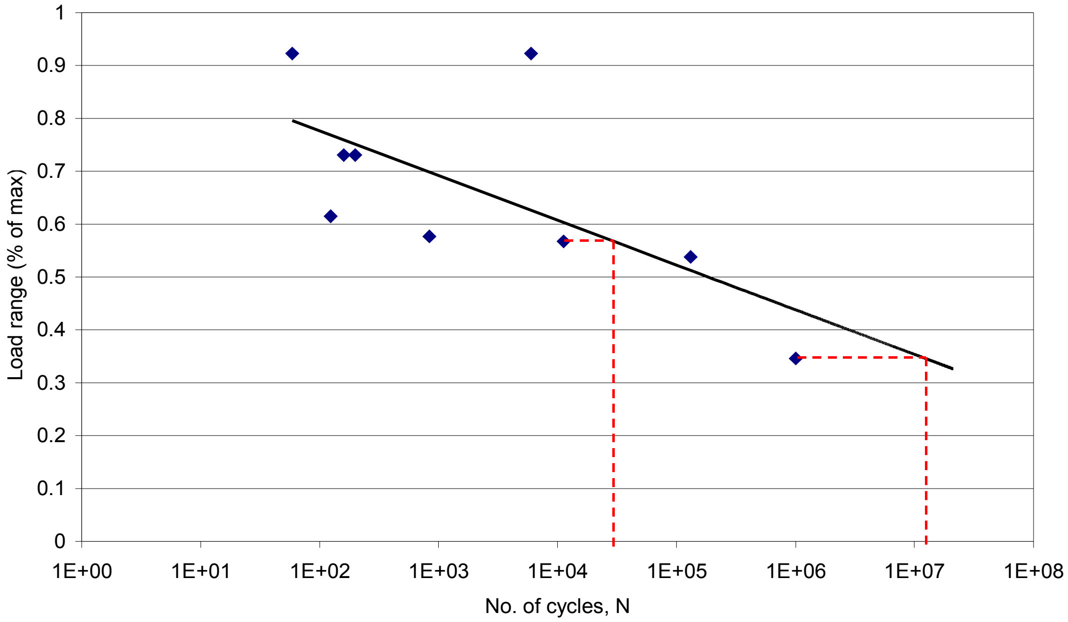
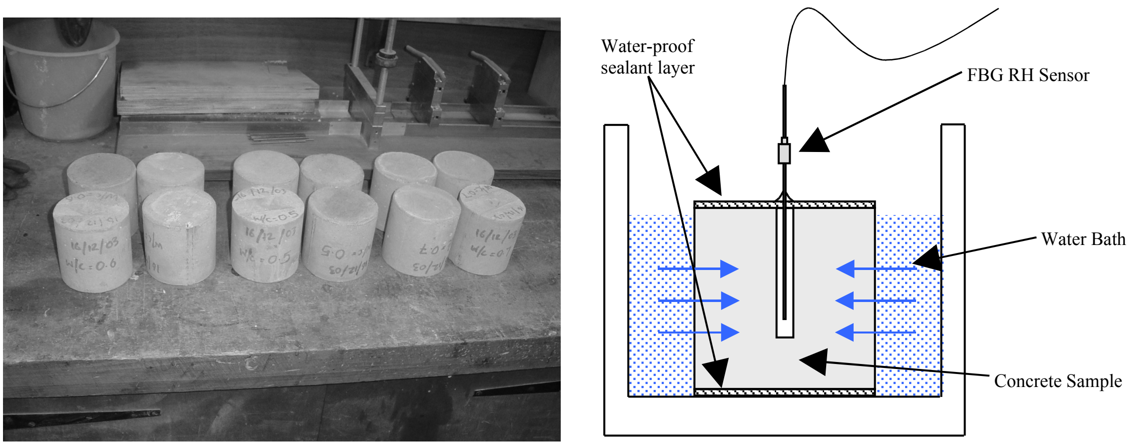


Figure 5. Fatigue curve for concrete beam specimens tested.



(a) (b)

Figure 6. a: Standardized cylindrical concrete samples of different water/cement ratio.
b: Schematic of a concrete sample with a RH sensor in the water bath.

3.5. Bridge Monitoring using an Optical Fibre Monitoring System.

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.

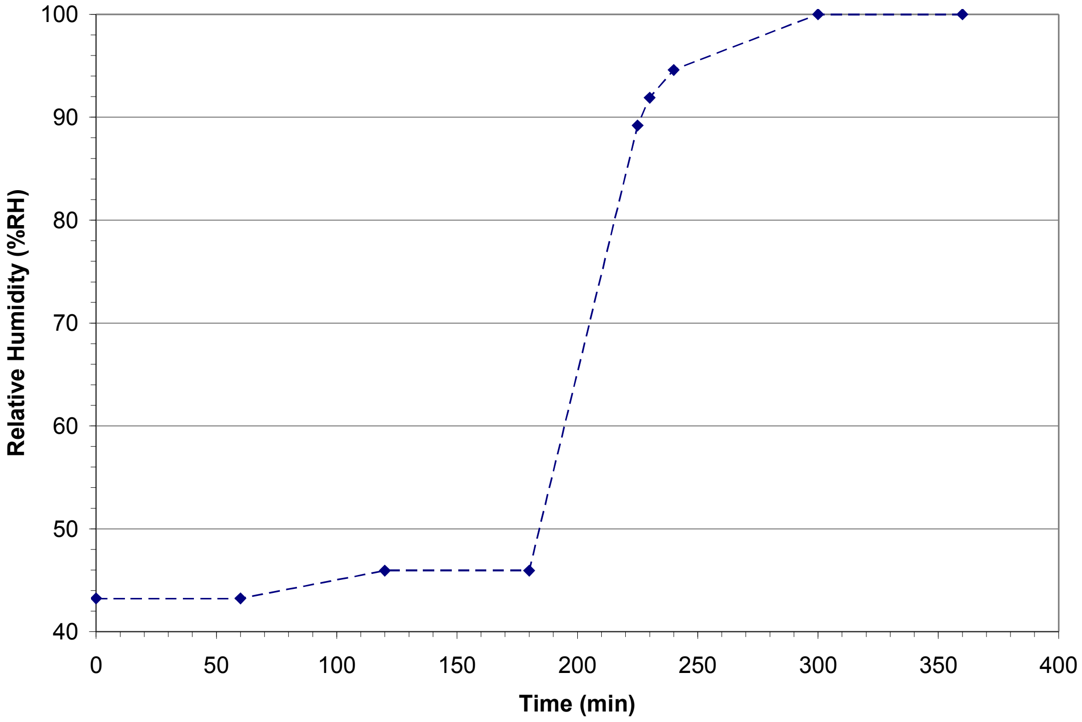


Figure 7a. Sample with w/c ratio of 0.6, oven dried at 80°C for 24 hours.

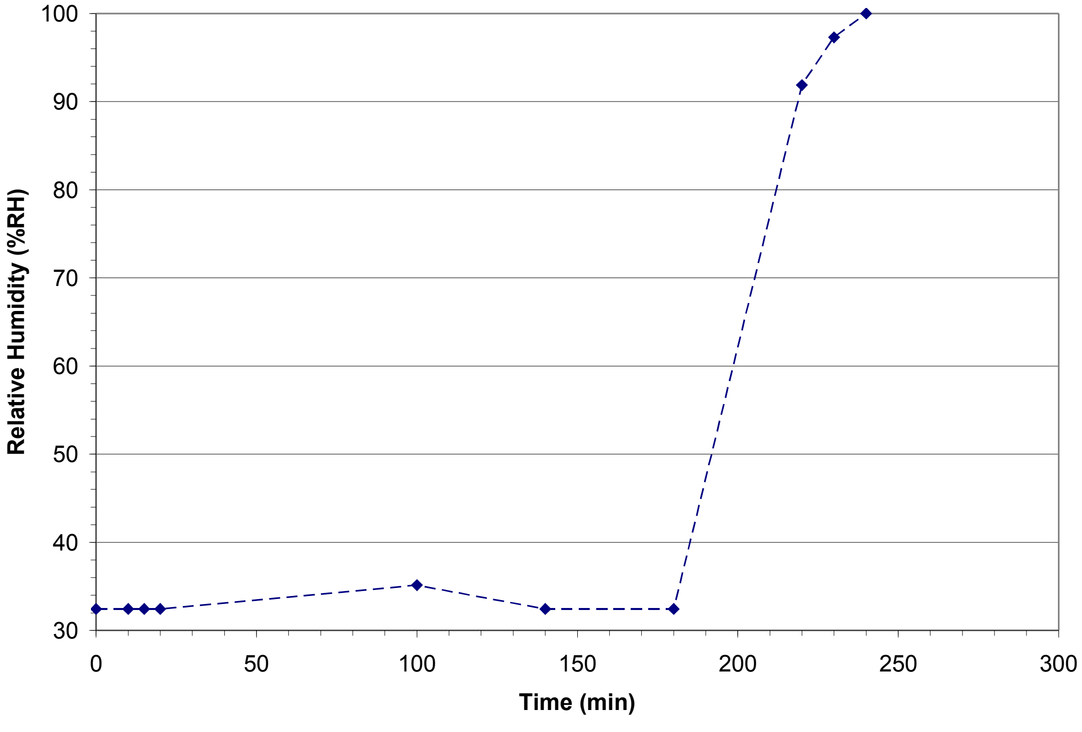


Figure 7b. Sample with w/c ratio of 0.7, oven dried at 80°C for 24 hours.

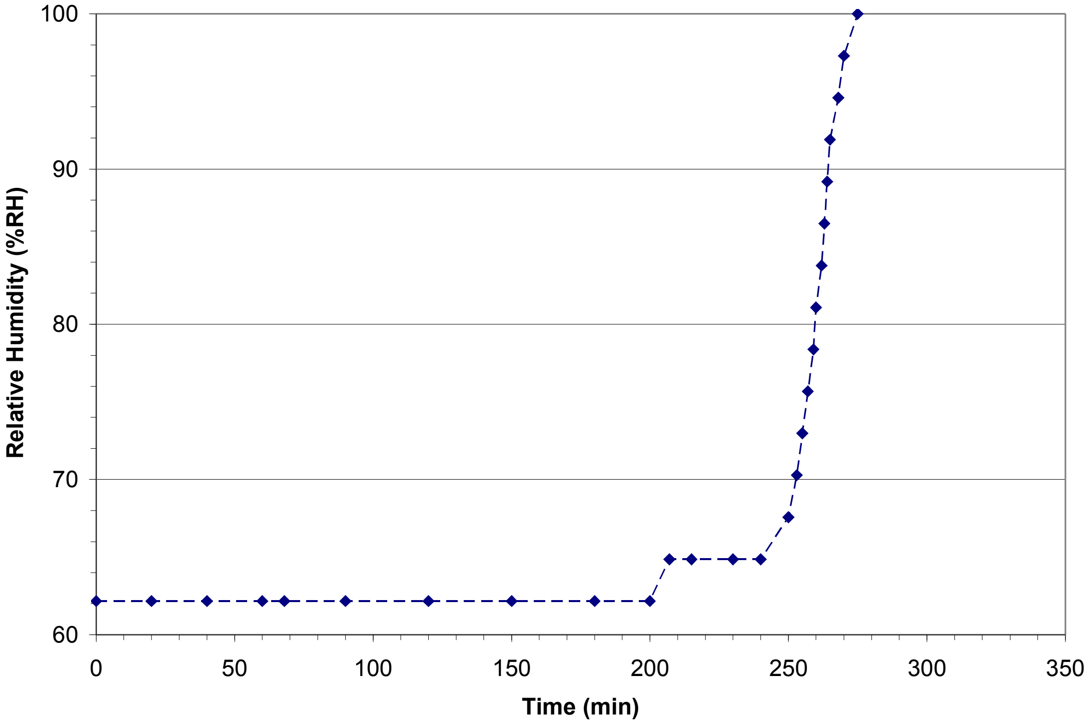


Figure 7c. Sample with w/c ratio of 0.5, oven dried at 95°C for 48 hours.

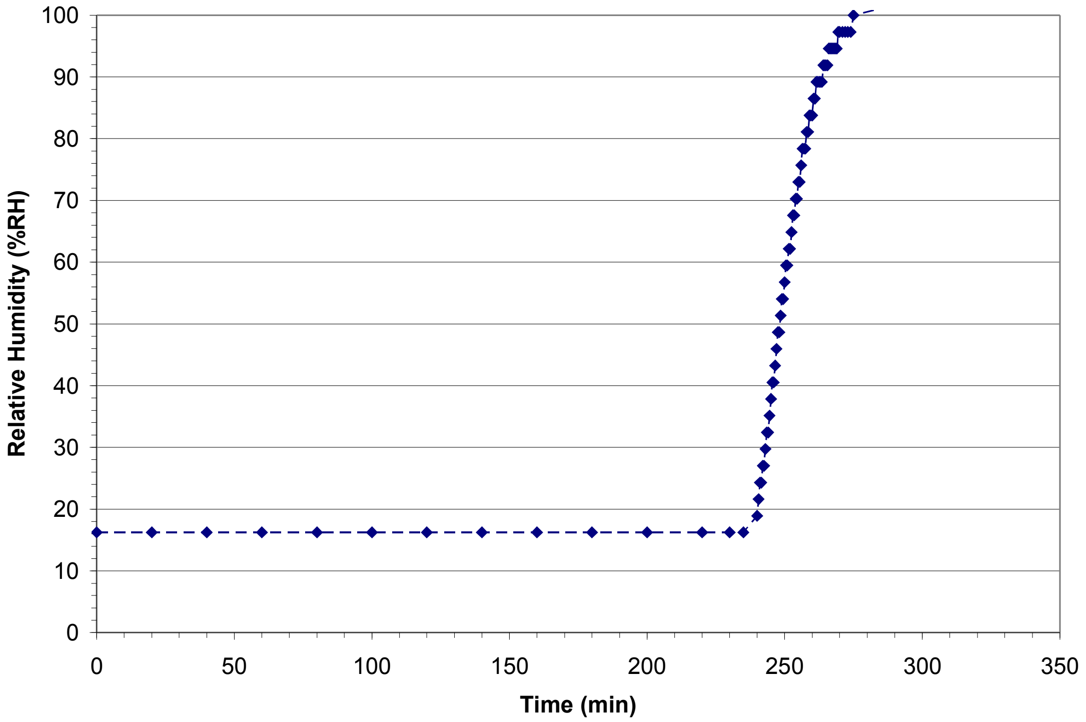


Figure 7d. Sample with w/c ratio of 0.7, Oven dried at 95°C for 48 hours.

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.

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.

4. Comparison of Theoretical and Acquired Data

Figure 8 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.

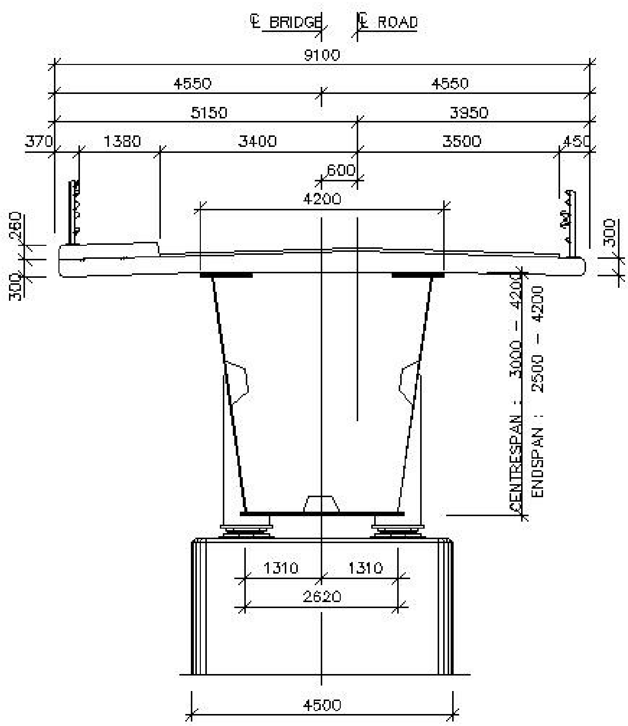


Figure 8. Typical cross-section of bridge.

5. Monitoring the effect of shield advance 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 9. Some typical results for the settlement along the axis of the NTT tunnel are shown in Figure 10.

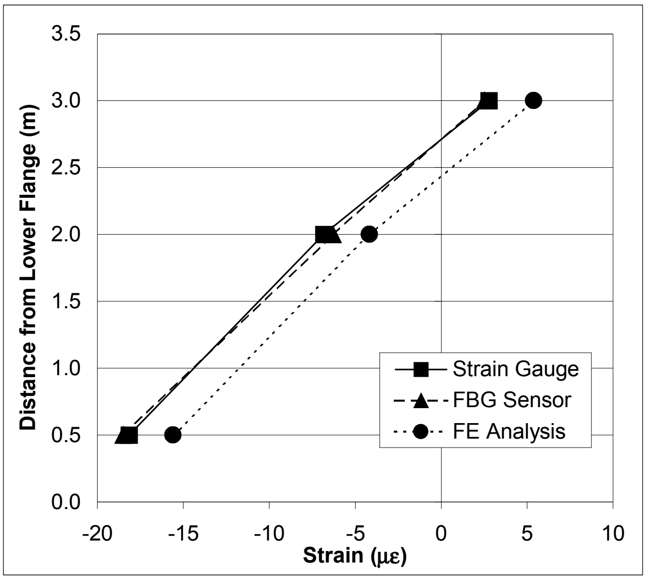


Figure 9. Comparison of data at support location (high shear loads).

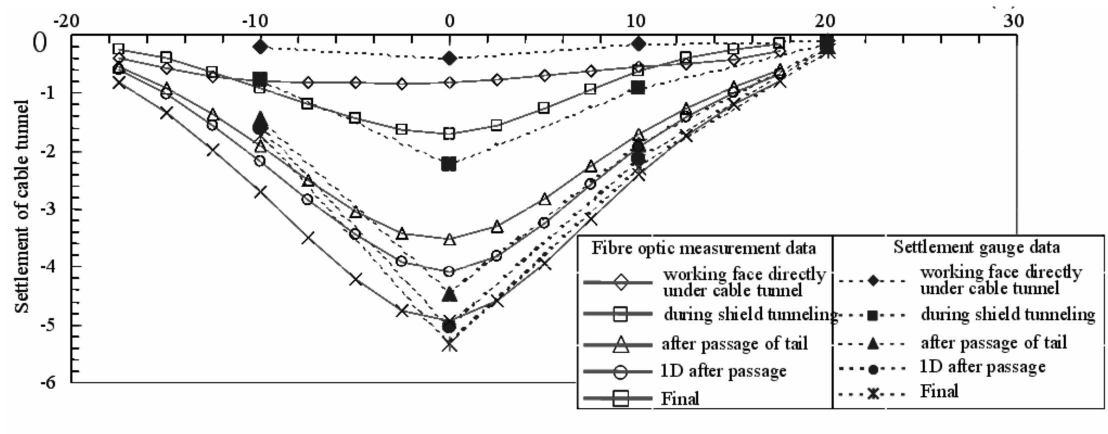


Fig-10 measured Settlement along the axis of the cable tunnel

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.

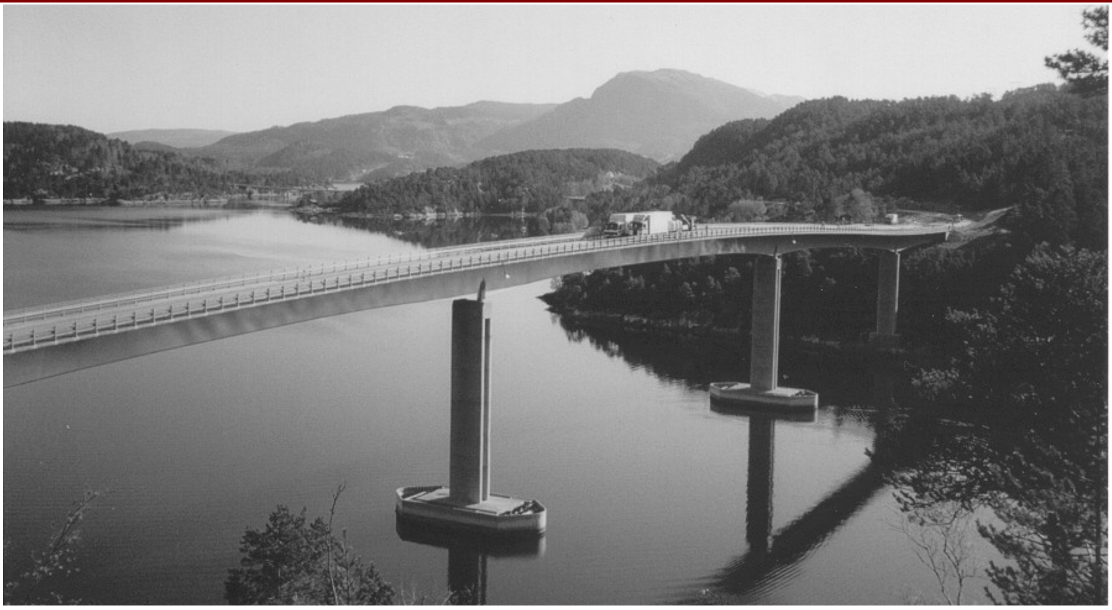


Figure 11. Mjosundet bridge used for the field trials.

6. 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. Sensors are also being used to determine the effectiveness of concrete repairs.

7. References

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