SS-5 Invited

Monitoring of large structures for safety issues using Brillouin distributed sensing

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Brillouin time-domain analysis in optical fibres is a novel technique making possible a distributed measurement of temperature and strain over long distance and will deeply modify our view about monitoring large structures, such as dams, bridges, tunnels and pipelines.

Optical fibre sensors based on stimulated Brillouin scattering have now clearly demonstrated their excellent capability for long-range distributed strain and temperature measurements. The Brillouin interaction causes the coupling between optical and acoustical waves when a resonance condition is fulfilled. It turns out that this resonance condition is strain and temperature-dependent, so that determining the resonance frequency directly provides a measure of temperature or strain.

The resonance frequency is an intrinsic property of the material that may be observed in any silica fibre. This is very attractive since the bare fibre itself acts as sensing element without any special fibre processing or preparation. Standard optical cables may thus be used, resulting in a low-cost sensing element that may be left in the structure. Since the optical effect only depends on the fibre material, it is absolutely stable in time and independent of the instrument. Different measurements performed over a long-term period are thus fully comparable.

The spatial resolution obtained with this equipment is 1 meter for a 10 km range. The physical limit for spatial resolution, that is just below 1 meter and results from the acoustic properties of silica, is actually reached by the equipment for short measurement range (< 1 km). This configuration of the sensor is thus definitely dedicated for long range measurements with meter resolution and is not suitable for centimeter resolution. It must be pointed out that a novel and very inventive configuration was recently reported by K.Hotate *et al*, based on a correlation technique, that achieved measurements with a 1 cm spatial resolution, but the range is also reduced to less than 1 km, accordingly.

The accuracy on the determination of the Brillouin shift ν_B depends on the amplification contrast and the probe signal intensity. In standard fibres an accuracy of 1 MHz is observed. This approximately corresponds to a 1 K temperature resolution and to a 2×10^{-5} strain resolution. The Brillouin shift accuracy can be improved to 250 kHz, corresponding to a 0.25 degC temperature and 5×10^{-6} strain resolutions, respectively, at the expense of either a worse spatial resolution or a longer measurement time.

The Brillouin time-domain analysis was first developed to detect local strains in telecommunication cables, which may cause early failure due to fibre breaking. It turned out that this application has gained little interest, the manufacturing quality of telecom cables making the optical fibre to show practically no strain.

But the special threadlike geometry of the optical fibre makes it an excellent candidate for monitoring large structures and installations. This property clearly opens new opportunities for a better control of the natural or built environment. The distributed nature of the sensing element offers the possibility to densely control a structure over its entire length, surface or volume, which would be impossible using point sensors.

We had the opportunity these past few years to perform many measurements on different sites. In all cases the sensor demonstrated its capability to perform the required measurements, in few cases at the expense of a special installation or packaging of the fibre.

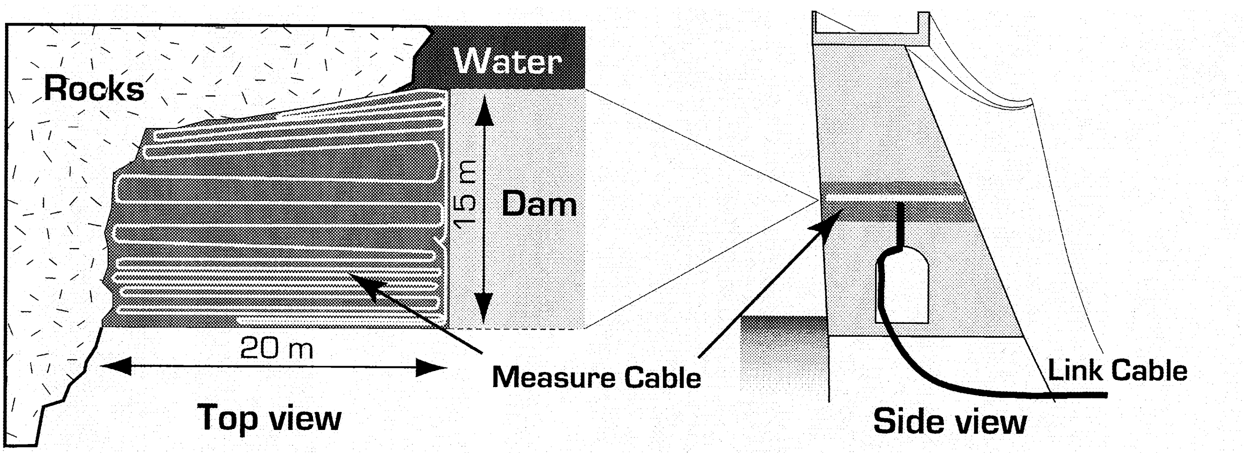
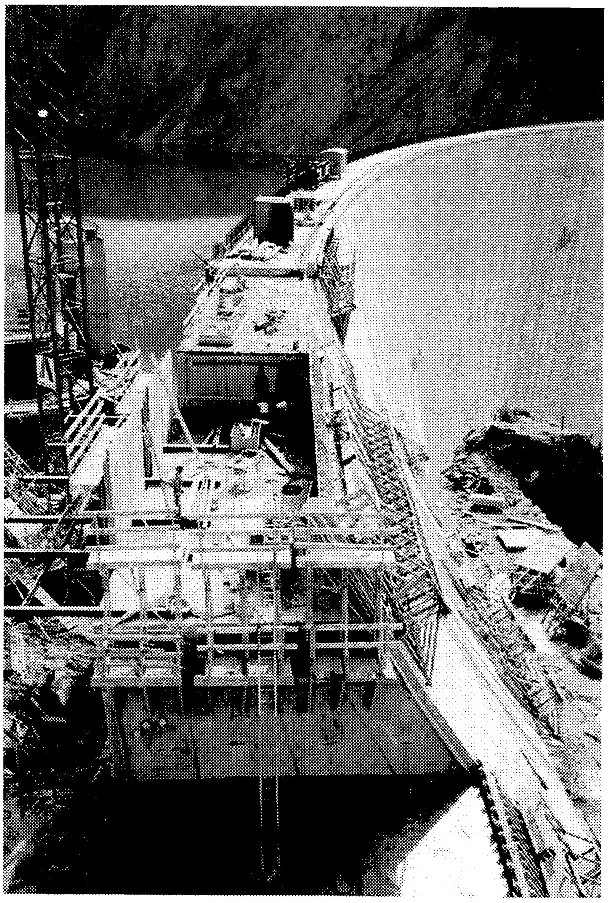


Fig 1 View of the concrete slab and of the mat-like installation of the measuring cable for concreting temperature monitoring, during the raising of Luzzone dam in the Swiss Alps

Concrete temperature monitoring in a dam

The first application reported here was performed in 1997 in a real environment and uses the optical fibre as a temperature probe. The equipment was used to monitor the concrete setting temperature in large structures. This monitoring is of prime importance in critical works, since the density and the importance of microcracks are directly related to the maximum temperature experienced by the concrete during the setting chemical process.



A major dam at Luzzone in the Swiss Alps was recently raised to increase the power capability of the associated hydroelectric plant. This raising was actually achieved by gradually stacking new concrete slabs of 15 m x 10 m average size for a 3 m thickness, as shown in Fig. 1. A small optical telecommunication cable was installed during the concreting over the central layer of the largest slab, so that the embedded cable makes a dense horizontal mat, necessary to obtain a two-dimensional temperature distribution of the whole slab area. Fig. 2 shows the temperature distribution over the slab at different moment after concreting. It can be clearly seen that the temperature rises up to 50 degC in the central area and that it takes many months to

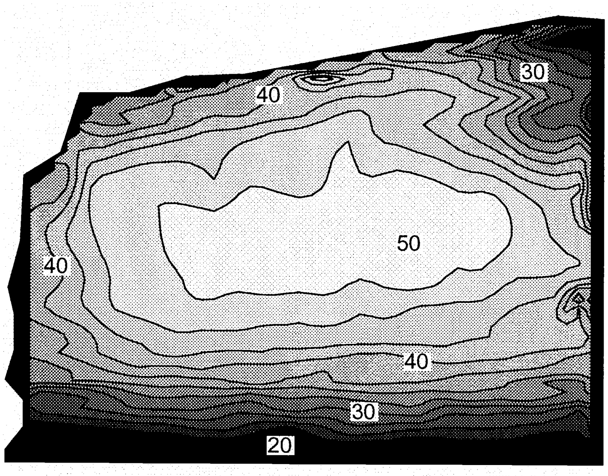


Fig.2 Temperature of a 20x13x3m concrete structure in a dam, performed 30 days after concreting. Isotherms are shown in degree centigrade.

cool down this region. The outer slab areas rapidly stabilize at the ambient temperature, so that an observer is totally unaware that the concrete is still fairly hot in the central region of the dam.

Secure tunnelling using smart reinforcing pipes

Constructions such tunnels in unstable soils may lead to severe safety issues. Numerous tragedies during the construction process were reported in the past. This issue is particularly present in Eastern Asia and techniques based on the installation of reinforcing bars are now commonly used.

The possibility to use the reinforcing tools as sensing elements turned out to be very attractive, since it offers the opportunity to inform on the soil movements during the construction in real time. Brillouin local analysis of strain turns out to be very convenient for this application, since the fibre may be installed to replace many points sensors and thus to fully inform on the deformations experienced by the reinforcing pipes. In addition the fibres from different pipes may be serially connected, so that the entire site may be controlled in a single measurement process.

The fibre was placed longitudinally along the pipe and at each cardinal point on the section, as shown in Fig. 3. In case of moving unstable soils the pipe is subject to flexure and fibres placed on opposite sides of the pipe experience symmetric and opposite strains (elongation-compression). This makes possible to subtract any offset due to temperature and residual strains resulting from the installation.

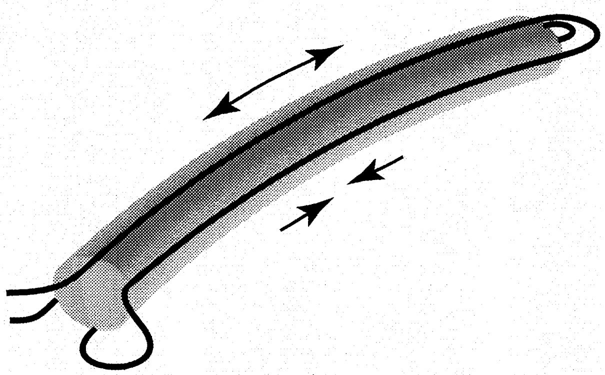


Fig 3 Schematic view of the smart reinforcing pipe used for strengthening the soil during excavation. The fibre is placed at the four cardinal points of the pipe section and experiences strain whatever the direction the pipe is deformed by soil movements.

Fig 4 Installation of a reinforcing pipe containing fibres as strain sensor in the Ulsan-Kangdong tunnel.

The fibre optic sensor system was tested in the Ulsan-Kangdong tunnel in Korea, that is a section of a national road under construction. The system is used to predict the behaviour of the tunnel section during and after excavation.

During tunnelling, most of the tunnel deformation is observed within 1 day after tunnel excavation. The smart pipe thus offers a key advantage with respect to conventional techniques as far as safety is concerned, since it informs immediately after installation.

As a result of the fibre placement the response to strain of the smart reinforcing pipe is symmetric with respect to the centre line. This is clearly shown in Fig 5, which is a typical measurement of the response of a smart reinforcing pipe during excavation in the Ulsan-Kangdong tunnel.

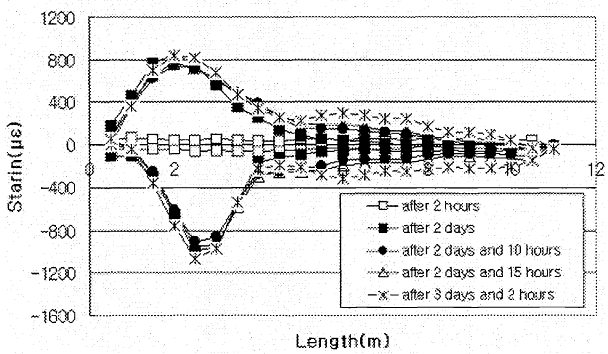


Fig 5 Distribution of strain along the smart reinforcing pipe for 2 fibres placed on opposite sides, showing a symmetric deformation. The deformation process stops after 2 days and remains steady.

From these strain data, the stress and displacement of the reinforcing pipe are calculated, giving important information to predict issues about the tunnel safety. As shown in Fig 5, large variations of the pipe deformation occurred just after tunnel excavation, within 2 days. Then the strain response remains steady, meaning that the tunnel deformation has stopped and the tunnel may be considered as safe.

Pipeline leakage detection

The next application is based on distributed temperature sensing using Brillouin analysis and demonstrates that the long range capability of this technique may lead to a very efficient and cost-effective solution.

The site is situated near Berlin in Germany and is related to the construction of a gas storage facility in a salt mine. This necessitates the cleaning of the mine using hot water and the subsequent evacuation of the brine produced by this cleaning. For this purpose a 55 km pipeline was installed and a leakage detection system was mandatory required for environmental reasons. A fibre optics Brillouin system was selected for the leakage monitoring according to the key advantages offered by the technique.

In this case the leakage detection is based on the recording of the temperature profiles of a fibre placed in sand just under the pipeline. Any leakage will result in a local increase of temperature, since the brine is significantly heated to improve its fluidity. The pipeline operator required that the effective spatial resolution must be 2 m, the temperature accuracy 1 degC and the measurement time less than 5 minutes.

According to these requirements the leakage monitoring system was designed using 2 Brillouin analysers, each of them controlling 2 sections of fibre, so that the entire 55 km pipeline is controlled by 4 sections of fibre, as shown in Fig. 6.

Fig. 7 shows a detailed view of a temperature profile on a 500 m segment of the pipeline. In this segment the presence of splice boxes placed over the ground surface (winter temperature of 0 deg) shows the accuracy of the system in terms of spatial and temperature resolution.

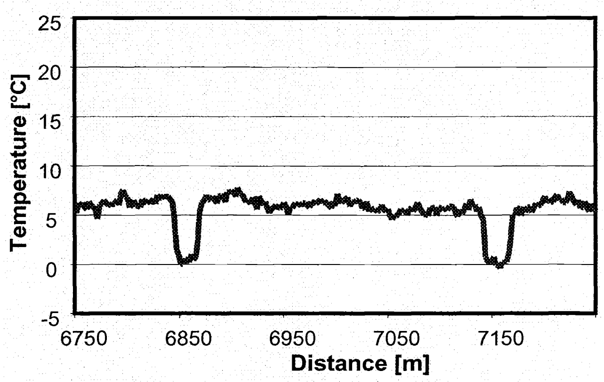


Fig 7 Temperature profile of a 500 m segment of the pipeline. Presence of splice boxes at air temperature (0 degC) is clearly observed. Any leakage would rise the temperature of more than 20 degC.

The system now works for more than 10 months in an entirely unattended and fail-safe continuous operation. This demonstrates a typical niche application in which a distributed long range fibre system offers decisive advantages.

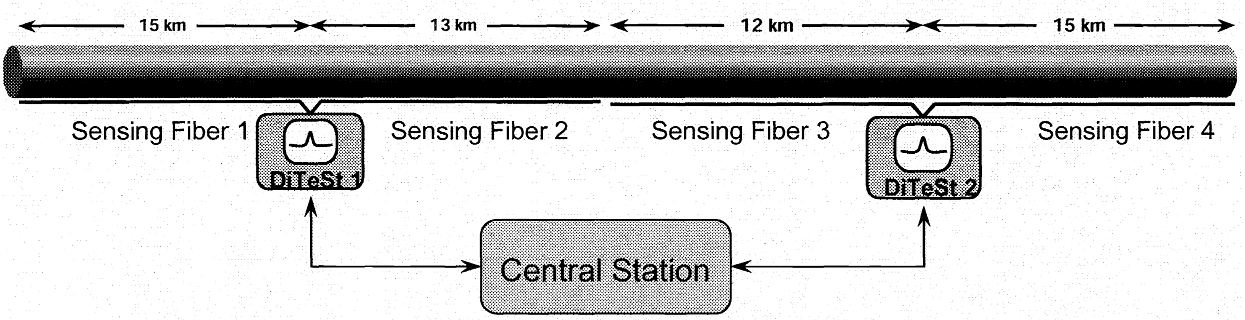


Fig 6 Schematic view of the leakage monitoring system for the 55 km brine pipeline near Berlin. The system uses 4 segments of cabled fibres and only requires 2 Brillouin analysers (Omnisens DiTeSt STA201C).