

Existing crack monitoring by distributed optical fiber sensors

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ABSTRACT: The distributed optical fiber sensor is expected to be one of the best candidates for monitoring an underground repository for radioactive waste because of its multiplexing ability and long-term durability. The recent development of Brillouin-based sensing can achieve distributed strain information with high spatial resolution. For a field experiment in a deep underground tunnel, an optical fiber sensor was installed on a mock-up concrete pit that simulates the low-diffusion layer in a waste repository. On the surface of the concrete, an optical fiber was attached along the entire length for strain sensing, crossing some existing cracks. As a result of the year-long measurement, widening of the cracks was detected by the distributed strain information. The Brillouin-based optical fiber sensor can successfully reveal the existing crack behavior, which is slight opening of the crack tip in the cold and closing in the heat. Such temperature-dependent behavior is derived from the thermal expansion of concrete, and therefore the crack tip opening displacement may be influenced by the size or depth of the crack. This study experimentally indicates that the distributed optical fiber sensor can not only detect the occurrence of a new crack, but also identify an existing crack for assessment.

1 INTRODUCTIONS

For monitoring at a nuclear waste disposal site, long-term durability and distributed measurements are essential. The site must be securely monitored for an extremely long time, perhaps centuries or longer. Although multiple measurements on shielding structures are favorable, through-holes for wiring are limited to avoid leakage of radiation. A distributed optical fiber sensor (OFS) that is based on Brillouin or Rayleigh scattering has the potential to overcome these obstacles, as described in an existing study (Imai *et al.*, 2018).

To investigate the potential of distributed OFS for strain measurement in an underground repository, on-site measurement is certainly important. Optical insertion loss will result in poor measurement accuracy of the distributed OFS, or in no observed signal in the case of severe conditions. Optical insertion loss depends on both the property of the optical cable and the conditions of the installation. In terms of the installation conditions, a laboratory test is insufficient to evaluate the on-site performance of the optical fiber. Therefore, the authors executed the on-site measurement on a mock-up concrete pit in a deep underground tunnel.

It is expected that the Brillouin-based distributed measurement will mainly detect the occurrence and development of cracks in a low-diffusion layer that is made of concrete, because crack opening weakens the barrier. On the other hand, a surface crack is known to open and close because of seasonal variations. In this study, the authors installed an optical fiber on a



mock-up concrete pit and measured strain distribution, and then confirmed the ability of the optical fiber to determine the crack opening behavior.

2 EXISTING CRACK MONITORING

2.1 Monitored structures

2.1.1 Mock-up concrete pit

A mock-up concrete pit, which simulates the low-diffusion layer of a radioactive waste repository, had been built at the dead end of a deep underground tunnel in the northern part of Japan. As shown in Figure 1, the concrete pit has a prism shape, and is 13 m wide, 12 m high, and 14 m long. For years, various experiments developed for a radioactive depository facility have been executed in the pit, for example those of Sasaki *et al.* (2009). Through the construction of the pit, the design, material, and construction process have been experimentally evaluated on-site. Moreover, techniques developed for the long term, including monitoring techniques, have been continuously evaluated since construction.



Figure 1. Mock-up of concrete pit in tunnel

2.1.2 Optical fiber installation

For the experimental evaluation of optical fiber (OF) measurement in the mock-up pit, OF cables were placed on the top and left surfaces of the pit with two-component epoxy. Each cable had one single-mode 1.8 x 3.5 mm fiber and two glass fibers reinforced with plastic for strength, as shown in Figure 2.

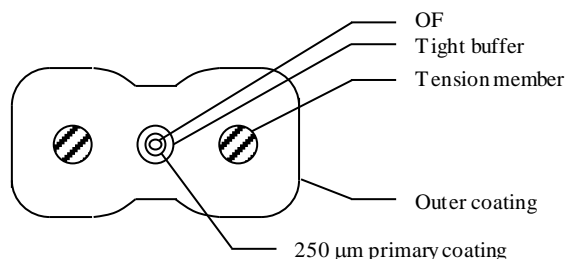


Figure 2. OF cable cross-section

On the left side of the pit, three cracks existed already. The OF cable was attached on the surface and laid across the cracks. As shown in Figure 3, the cable was laid in a serpentine pattern, starting and ending at the same location.

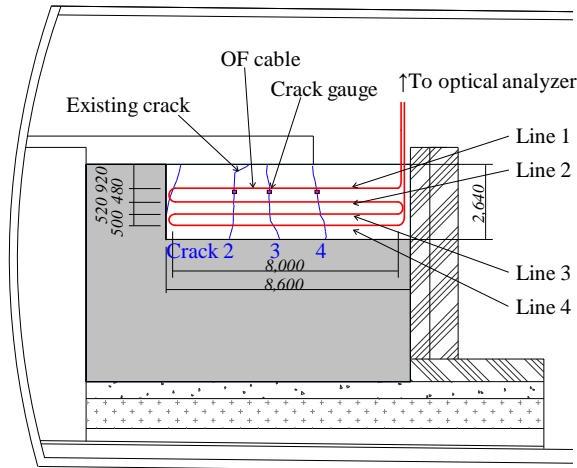


Figure 3. OF configuration of left side of pit

On the top surface of the pit, one crack existed already. The OF cable was attached to the surface, making a grid with 30 cm intervals as shown in Figure 4. Figure 5 shows the installed OF cable.

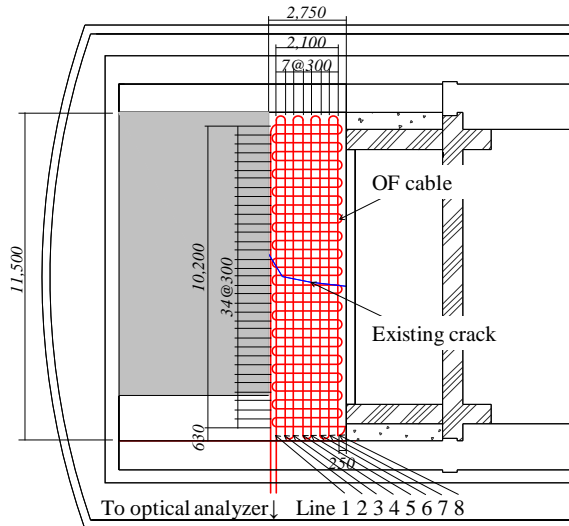


Figure 4. OF configuration of top surface of pit



Figure 5. OF cable installation on top

All ends of the OF cable were extended for approximately 170 m to the optical analyzer, which was installed in a housing in the tunnel.

2.2 Strain measurement

2.2.1 Brillouin-based measurement

There are many types of measurement methods that are based on Brillouin scattering. Because of its applicability, simultaneous Brillouin scattering, which is generated by an injected light wave, has been widely used with a single-end configuration, for instance in Brillouin optical time domain reflectometry (BOTDR). On the other hand, stimulated Brillouin scattering produces higher signals with the use of two encountered light waves, although a complicated (double-end) optical fiber configuration is necessary. In this study, higher spatial resolution is required to detect the crack opening displacement (COD). One of the methods based on stimulated Brillouin scattering, pulse-prepump Brillouin optical time domain analysis (PPP-BOTDA) was used, as illustrated in Figure 6 (Kishida *et al.*, 2005). Observed Brillouin frequency shift change is expressed by the following equation with constants (C_{11} and C_{12}), where $\Delta\varepsilon$ and ΔT are changes in strain and temperature, respectively.

$$\Delta\nu_B = C_{11}\Delta\varepsilon + C_{12}\Delta T \quad (1)$$

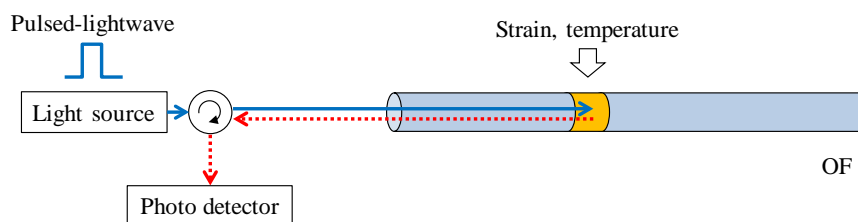


Figure 6. PPP-BOTDA system

2.2.2 Crack gauge

To determine the behavior of an existing crack, three crack gauges were installed on the existing crack, as shown in Figure 3. The base of the crack gauge was attached to the concrete with two-component epoxy as shown in Figure 7. To prevent an unexpected impact on crack behavior, anchor pins to fix the base were deliberately avoided.



Figure 7. Installed crack gauge

2.2.3 Long-term monitoring

Along the installed OF cable on both the top and the left surfaces of the pit, the distribution strain was periodically measured for a year by a PPP-BOTDA analyzer, which was placed in the housing as shown in Figure 8. Measurement parameters are tabulated in Table 1. In addition, displacements of the three crack gauges and the air temperature at the bottom of the pit were continuously measured by conventional electrical instruments.



Figure 8. Optical analyzer

Table 1. Measurement parameters

	Left	Top
Fiber length (m)	380	540
Spatial resolution (mm)	100	100
Spatial interval (mm)	50	50
Initial measurement	11:27, 1 Jan. '18	11:53, 1 Jan. '18
Measurement interval (min)	180	180

2.3 Results and discussions

2.3.1 Strain distribution

Measurement results for the left side are shown in Figure 9 for various measurement times. The results are plotted as Brillouin frequency shift (BFS), and therefore the temperature effect and pre-tensioning strain at installation are included. Measured results for the region of the OF bends and extensions show larger changes than those for the attached region (Line 1, 2, 3 and 4), because at the bends and extensions the OF is not constrained and responds freely to temperature changes. The BFS clearly changes locally at the three existing cracks (Crack 2, 3 and 4), and the BFS at those locations decreases during summer.

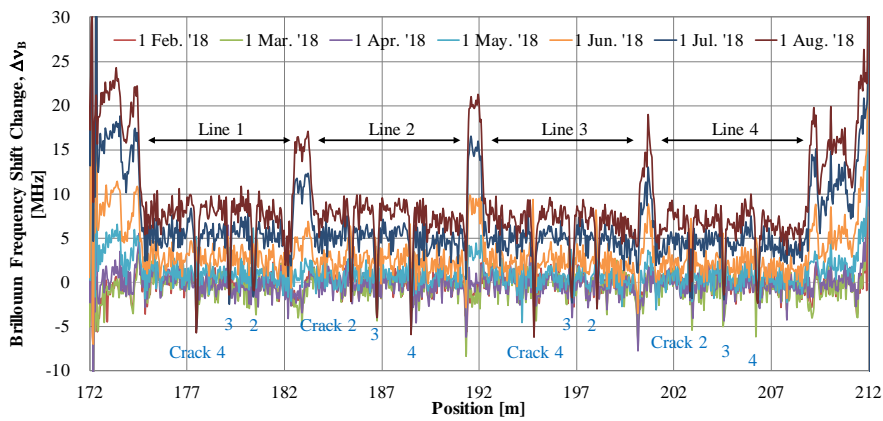


Figure 9. Measured strain distribution on left side of pit

Measurement results for the top surface are shown in Figure 10 for various measurement times. As in the previous figure, the results are plotted as BFS, and therefore the temperature effect and pre-tensioning strain at installation are included. As with the left-side measurements, the BFS clearly changes locally at the one existing crack, and the BFS at that location decreases during summer.

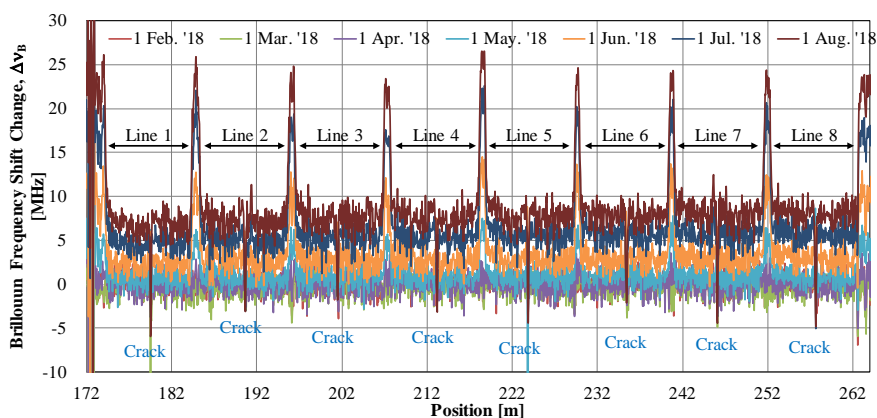


Figure 10. Measured strain distribution on top surface of pit

2.3.2 Measured crack behavior

COD values measured by the crack gauges are plotted in Figure 11, together with the temperature change. The bases of the crack gauges detached from the concrete because of high

humidity of the ambient air near the concrete pit. The humid air led to condensed water on the colder concrete pit in the summer. The crack gauges were re-attached, but detached again. With detachment, the quantitative value of COD is meaningless; however, the measured trend does show the inverse relationship with temperature. The COD is experimentally demonstrated to open in cold conditions, and close in hotter conditions.

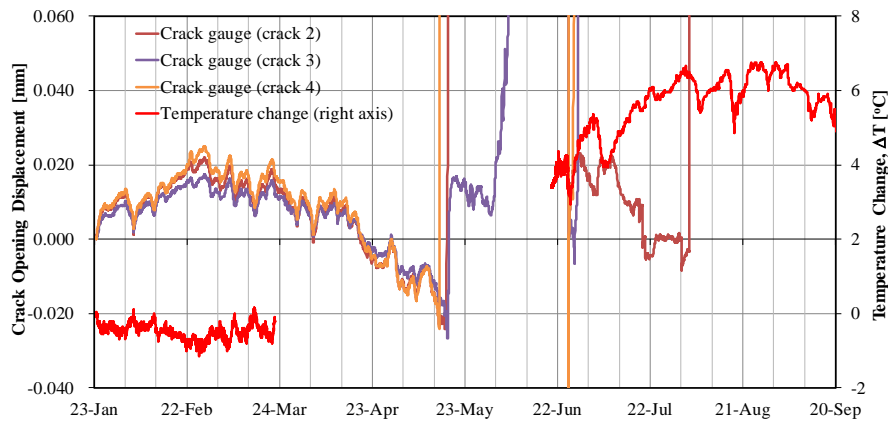


Figure 11. Time history of COD and temperature on left side of pit

Together with the temperature measurement, the time histories of the measured BFS for the existing crack #4 of the left side are presented in Figure 12. The four OF results that correspond to the location of crack #4 all behave similarly and correlate well with temperature. Although the existing literature shows that distributed OFS can detect COD (Imai *et al.*, 2010), COD by seasonal temperature trend has never been experimentally demonstrated.

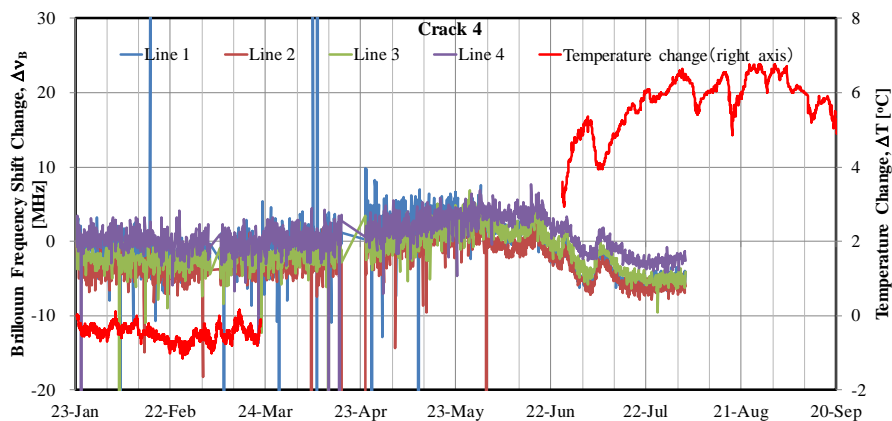


Figure 12. Time history of OF measurement and temperature on left side of pit

Based on Figure 12, the relationship between temperature change and OF measurement are shown in Figure 13. There is no rebar in the monitored structure which simulates the low-diffusion layer in a waste repository, and such crack behavior is derived from thermal expansion of concrete. Thus, the behavior is expected to be indicative of the size or depth of the existing crack.

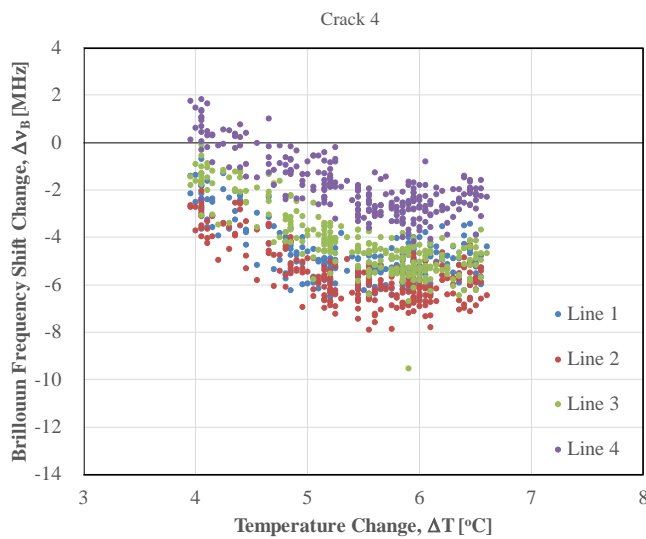


Figure 13. Time history of OF measurement and temperature on left side of pit

3 CONCLUSIONS

For monitoring an underground repository for radioactive waste, a distributed optical fiber sensor is promising, because of its unique properties such as long-term durability and multiplexing ability. To evaluate the performance of a Brillouin-based OF in situ, the authors installed an OF cable at a mock-up facility for long-term strain measurement. Experimentally, the OF measurements demonstrated the crack opening displacement caused by temperature variation. Such behavior of existing cracks has the potential to identify crack properties. To assess cracked structure accurately, this thermal behavior must be considered. Further experimental investigation is required to determine the width and depth of cracks based on OF measurements.

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