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Measurement of Movement in Multi-Layer Sprayed Lining using High Performance Fiber Reinforced Cement Composite (HPFRCC) with Multiple Cracks

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Abstract: The Hida Tunnel is a 10.7km long expressway located between the Hida Kiyomi IC and the Shirakawa-go IC on the Tokai-Hokuriku Expressway. Both the main tunnel and the evacuation tunnel are more than 10km long, but the construction period was shortened by simultaneous construction of facilities such as the widened part at the emergency parking areas, paving, etc. Therefore the lining concrete, which has a large effect on the overall construction period, was constructed in part by multi-layered sprayed lining to achieve a reduction in the construction period. This paper reports on the construction of the multi-layer sprayed lining at the emergency parking areas of the main tunnel, the results of measurements of the movements of the lining, etc.

1. Introduction

The Hida Tunnel is a 10.7km long expressway located between the Hida Kiyomi IC and the Shirakawa-go IC on the Tokai-Hokuriku Expressway. Construction commenced in 1996, but because of the complexity of the geological conditions and the effect of faults, the anticipated poor rock areas and hydrothermally altered areas were encountered everywhere, so excavation of the tunnel was extremely difficult. In March 2006 the advanced tunnel penetrated, in January 2007 the main tunnel penetrated, so more than 10 years were required from the start of construction. The tunnel opened in spring 2008, more than one year after penetration, so even though this was a long tunnel in excess of 10km, a shortening of the construction period was achieved by the method of simultaneously constructing the widened parts for the emergency car parking areas, the paving, construction of the various facilities, etc., and partially making the lining concrete, which has a large effect on the overall construction period, single shell lining.

In this paper, details of the design carried out in advance for the adoption of multi-layer sprayed lining at the emergency car parking areas of the main tunnel to shorten the construction period, details of tests on the steel fiber sprayed concrete secondary layer, and the results of quality control, etc., are discussed.

2. Investigation into Multi-layer Sprayed Lining at the Emergency Car Parking Areas

2.1 *Investigations of multi-layer sprayed linings*

The support function and the lining function of linings with the multi-layer lining structure using sprayed concrete cannot necessarily be clearly separated. Members such as a sheet that hinder the transmission of shear forces between the in-situ rock and the sprayed concrete or between sprayed concrete and sprayed concrete as used in conventional construction were not used, so there was a high probability that cracks will occur in the internal sprayed concrete layer. Therefore, to prevent harmful cracks, increase the overall safety and water tightness of the tunnel structure, and improve the durability, fiber reinforced sprayed concrete was used, with which there is a lot of experience in Europe in single shell linings, which is a structure close to that of the present multi-layer sprayed lining structure.

The sprayed concrete used in the multi-layer lining structure was developed and improved in large cross-section tunnels in the Second Tokyo-Nagoya Expressway (Daini Tomei Expressway) and the Nagoya-Kobe Expressway (Meishin Expressway), there is much experience in its use, including in evacuation tunnels, and there have been no quality problems. By using high strength fiber reinforced sprayed concrete, functionality and durability equal to or better than conventional tunnel linings can be obtained.

2.2 *Outline of the multi-layer sprayed lining structure*

Figures 1 and 2 show outline diagrams of the sprayed multi-layer lining structure. It was decided to provide a 50mm margin from the construction limit in the area with the multi-layer sprayed lining structure to allow for future repair thickness, so in areas where the conventional lining thickness would be 300mm, the 300mm of the current draft specification was reduced by 50mm, and a thickness of 250mm was investigated.

After excavation of the tunnel, and after the supporting structures and water seepage was processed, the secondary layer of steel fiber reinforced sprayed concrete was constructed, and the tertiary layer1) of high toughness mortar was applied with a trowel finish as a surface coating. The main functions required of each layer were as follows.

The structure consisted of the conventional primary layer as the primary support, the sprayed lining secondary layer, and the tertiary layer as the protective layer.

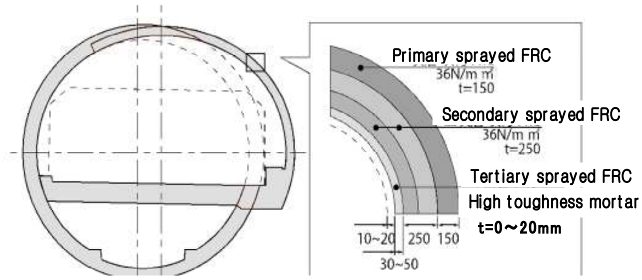


Fig. 1 Structure of each layer of the sprayed lining

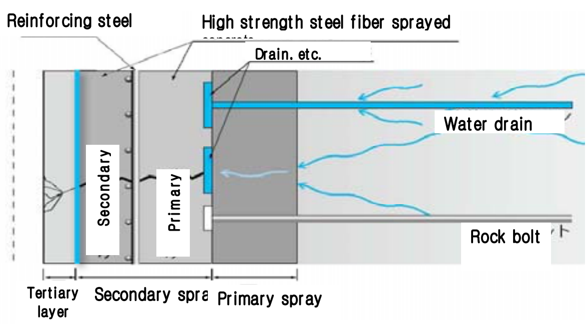


Fig. 2 Outline of the sprayed lining structure

2.2.1 *Primary layer performance requirements*

It is necessary that the sprayed concrete of the primary layer functions as both the primary support construction and as lining, so the following performance was required.

①The sprayed concrete must have sufficient axial compressive strength.

②The cracks that occur must be dispersed, so that the occurrence of cracks whose width is harmful is minimized.

Regarding durability, the primary layer is sandwiched between the in-situ rock and the secondary layer, so the environment for degradation is small, so it was decided not to add silica fume or similar. However, it was decided to use fiber reinforced concrete with non-metallic fibers so that the cracks that occur will be dispersed, and the occurrence of harmful crack widths will be suppressed.

2.2.2 *Secondary layer performance requirements*

It is necessary that the secondary layer sprayed concrete has the function of lining, so the following performance was required.

①There must be sufficient adhesion between layers.
②The sprayed concrete must have sufficient axial compressive strength.
③The long-term durability must be excellent.
④The lining must be capable of resisting bending and shear loads, and must maintain a high toughness stable structure even if cracks occur.

Taking the above into account, it was decided to add to the sprayed concrete steel fibers to improve the resistance to cracking and silica fume to reduce the porosity and improve the durability.

2.2.3 *Tertiary layer performance requirements*

The following performance was required from the materials of the tertiary layer1).

①The tertiary layer shall cover the whole surface, and protect the secondary layer from the external environment. (Durability)
② The tertiary layer shall repair cracks, etc., occurring in the secondary layer.
③ The tertiary layer shall form the final concavo-convex finishing surface. (Appearance)
④The tertiary layer shall have a water tightness function. (Waterproof)
⑤Degradation of the material itself shall be small with respect to physical and chemical action, and it is necessary that it has a protective function so that the function of the fiber reinforcement can be maintained for a long time. (Prevention of carbonation)
⑥ The tertiary layer shall prevent peeling and breaking away of the secondary layer sprayed concrete due to degradation. (Peeling and breaking away prevention function)

High performance fiber reinforced cement composite (HPFRCC) with multiple cracks was used as a material having these functions.

3. Outline of the Measurements on the Multi-Layer Lining

This was the first time a multi-layer lining with sprayed concrete in the secondary lining was adopted for the emergency car parking areas in a road tunnel in Japan. Therefore TDM FBG optical fiber sensing technology was adopted for strain measurement of the multi-layer lining, as this could be installed in thin layers of concrete over 10cm thick, and as it was necessary to carry out long term monitoring of the stability of the multi-layer lining, not only during construction, but also during service. As a result it was possible to determine the strain behavior of the multi-layer lining from the initial

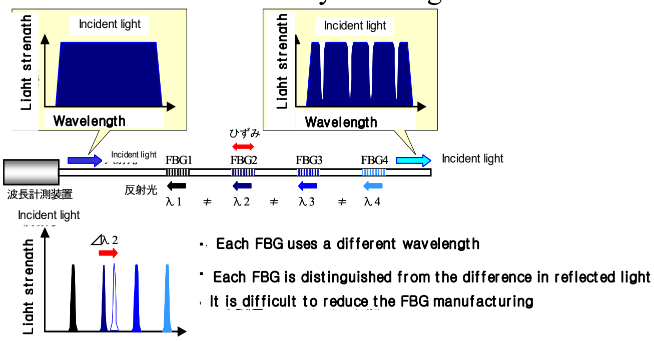


Fig. 3 Concept of multiplexing by the WDM method

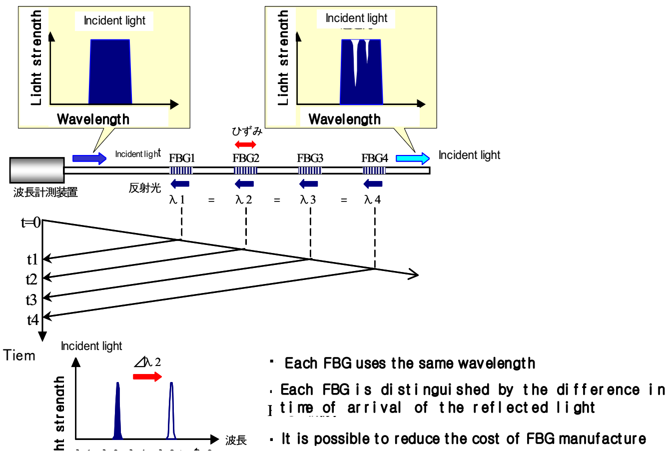


Fig. 4 Concept of multiplexing by the TDM method

stage immediately after spraying. In this paper, an outline of TDM FBG optical fiber sensing and its characteristics, an outline of the measurements on the multi-layer lining, and the measurement results are presented.

3.2 *TDM FBG optical fiber sensing*

Methods in which several FBG are arranged in series on a single optical fiber, and the reflected wavelength from each FBG is measured and multiplexed include the wavelength division multiplexing method (hereafter referred to as WDM) in which the measured wavelength axis is multiplexed, and the TDM method5) in which the time axis is multiplexed.

In the WDM method, as shown in Fig. 3, in the C band (1520-1570nm) in which the attenuation of light strength is small, several FBG are used, each with its own characteristic grating period, so it is possible to distinguish the positions that the FBG are arranged in. Therefore, the strain measurement range of the FBG becomes narrower the greater the number of FBG that are arranged in series. In other words, if there are 10 FBG installed in series, the potential strain measurement range is about 4,000μ, and if there are 20 FBG installed the range is reduced to about 2,000μ.

On the other hand, in the TDM method, as shown in Fig. 4, the several FBG are distinguished by the time difference of the reflected light from each FBG, so even if the FBG have the same grating period, they can be distinguished. Also, the measurement range of each FBG is constant at a maximum of 9,000μ, regardless of the number of FBD installed in series. When there is no optical damage due to fusion bonding of the optical fibers or connection of the connectors, a maximum of 100 FBG can be connected in series on one optical fiber.

Therefore in the TDM method, many FBG having the same reflected wavelength can be arranged in series, so the measurement system is simple. In this way it is possible to reduce the cost of manufacturing the FBG sensors and constructing the system compared with the WDM method.

4. Outline of the Measurements on the Multi-Layer Lining

4.1 *Objectives of the measurement*

The FBG optical fiber sensing location is at an emergency car parking area within the long road tunnel located in a mountainous area where the minimum temperature in winter is -10°C. The positions of the measurement cross-sections are shown in Fig. 5.

At the emergency car parking area that contains the measurement cross-sections, sprayed concrete is used as the permanent lining, and an emergency car parking area is provided at the same location for both directions, so the cross-section is larger (about 140m^2) than the normal case where there is an emergency car parking area on one side only. Also, the measurement location is about 235m in from the entrance to the tunnel, so the lining itself will be affected by variations in the external air temperature (-10°C or less in winter and 30°C or over in summer) and humidity. Further, about 10m from the emergency car parking area there is an

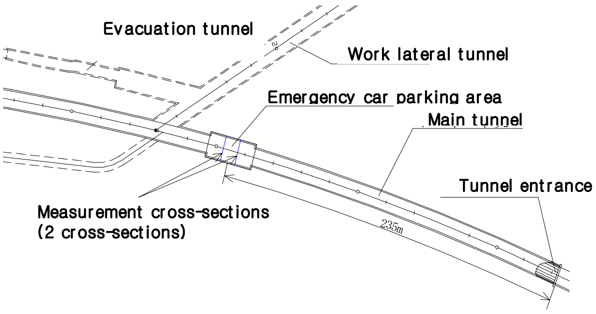


Fig. 5 Tunnel plan and location of measurement cross-sections

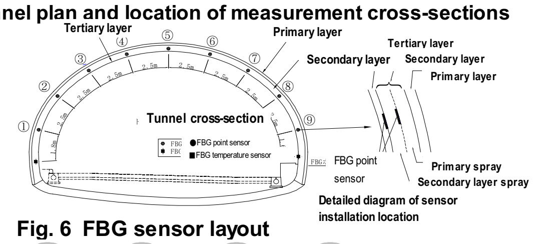


Fig. 6 FBG sensor layout

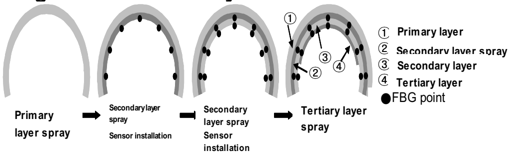


Fig. 7 Construction of the multi-layer lining and sensor installation sequence

intersection with a lateral tunnel, so these are conditions in which loose rocks or uneven soil pressure can occur.

As a result of the above it was decided to carry out long term measurements of the variations in strains generated in the multi-layer lining accompanying variations in the external air temperature and soil pressure at two cross-sections, with the objective of confirming the integrity of the multi-layer lining during construction and after commencement of service.

4.2 *Measurement positions and measurement details*

Figure 6 shows the FBG sensor layout, and Fig. 7 shows the sequence of multi-layer lining construction and sensor installation.

Of the multi-layer lining formed in a 3-layer structure as shown in Fig. 4, the strains generated in the secondary layer were measured using the FBG optical fiber sensors at the secondary layer primary spray surface and the secondary layer secondary spray surface. From their variation with time, it is possible to carry out long term monitoring of (1) daily and annual variations, (2) ground pressure, and whether uneven soil pressure has occurred or not, and (3) whether cracking has occurred or not, etc. The FBG point sensors used for measuring the construction strain were strip shaped sensors (length 250mm, width 25mm, thickness 4.5mm) that measure the surface strain of the concrete. These were fixed to the secondary layer primary spray surface and the secondary layer secondary spray surface at 2.5m intervals in the tunnel circumferential direction. Also, FBG temperature

Photo 1 View of measurement locations within the tunnel

sensor blocks were embedded both to measure the temperature within the multi-layer lining and the temperature within the tunnel, but also for temperature compensation of the FBG point sensors. The TDM type FBG optical fiber sensors were used for these measurements for the following two reasons.

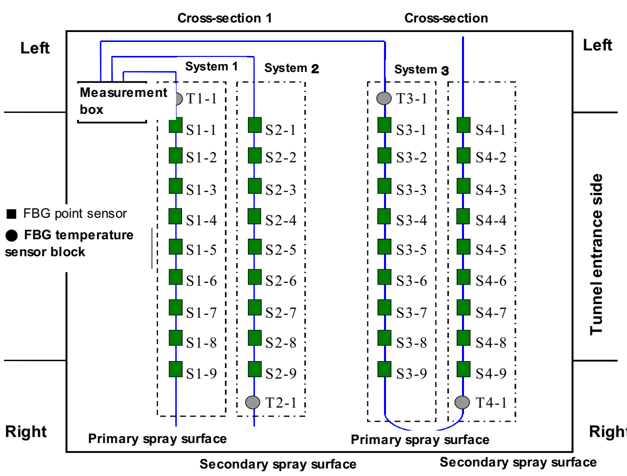
(1)By using the TDM method with many sensors arranged in series, only one cable is embedded within the multi-layer lining with thin layer thicknesses of 150mm for each spray layer in the secondary layer and 10mm in the tertiary layer.

(2)The material of the optical fiber that contains the sensors is quartz glass, which is essentially a high durability material. Also, the sensors are protected by FRP, so the degradation due to ingress of water is small compared with electrical measuring instruments.

Figure 8 shows a schematic diagram of the measuring system. All the optical fiber sensors (40 No.) were arranged into three systems to suit the spraying operations, system 1: 10 sensors, system 2: 10 sensors, and system 3: 20 sensors.

5. Measurement Results and Discussion

5.1 *Measurement Results*



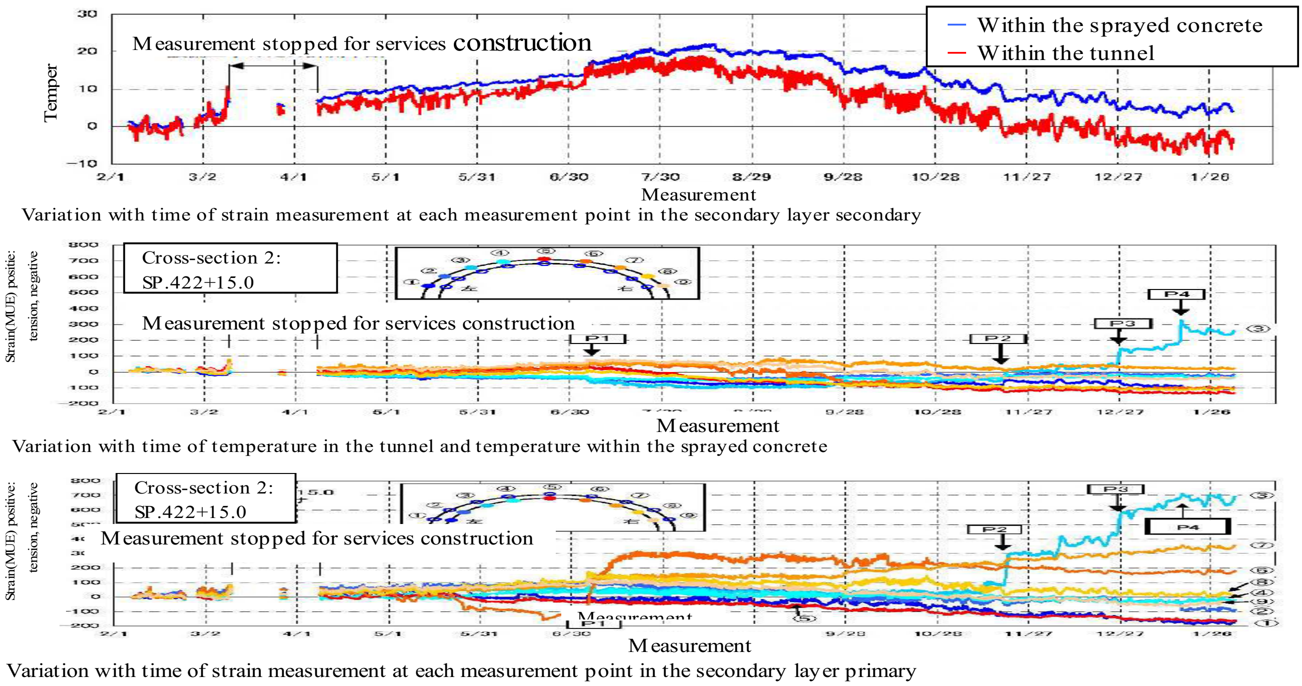


Fig. 9 Variation with time of measurement data at cross-section 2: SP.422+15.0

Measurement of the strains in the multi-layer sprayed lining commenced on November 7, 2007 when construction of the secondary layer secondary spray was completed. In this paper the initial value was taken on February 6, 2008 when the effect of temperature variations due to heat generation from the spraying operations had died down, and the strain variations in the subsequent one year are presented. Figure 9 shows the variation with time of the strain in the primary and secondary spray at measurement cross-section 2, together with the air emperature within the tunnel and the sprayed concrete temperature. Missing measurements in the figure are due to electricity stoppage for services construction in the tunnel.

From Fig. 9 it can be seen that in the one year from February 2008 to February the following year, the air temperature within the tunnel varied between the maximum of 19°C and the minimum of -7°C. Looking at the variation in strain at each measurement point in the primary spray, it can be seen that the variation is smaller than for the secondary spray, which is more easily affected by variations in the air temperature within the tunnel, and apart from measurement point ③, the variation was a maximum of about 100μ on the compression side from the initial value.

At the point P1 in the figure (July 5, 2008) the tunnel commenced service, and the air temperature within the tunnel varied, and associated with this the strain increased or decreased at all the measurement points for the primary spray and the secondary spray. In particular, it can be seen that at measurement point ⑥ on the secondary spray located on the right side of the top end, a variation of about 400μ on the tension side occurred. This is believed to be due to the effect of external constraint on the rear surface of the spray, as judged from the detection of the occurrence of a crack near measurement point ⑥ in a visual inspection carried out subsequently.

Next, at points P2 to P4, at measurement point ③ located at the left shoulder, it can be seen that the strain in both the primary and secondary spray changed to the tension side. At points P2 and P3 the variation in the strain of the secondary spray was

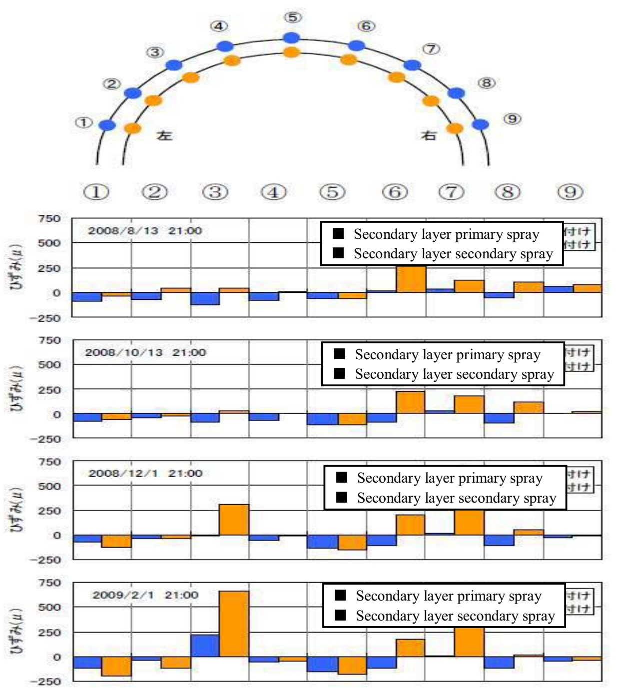


Fig. 10 Variation of strain distribution at measurement

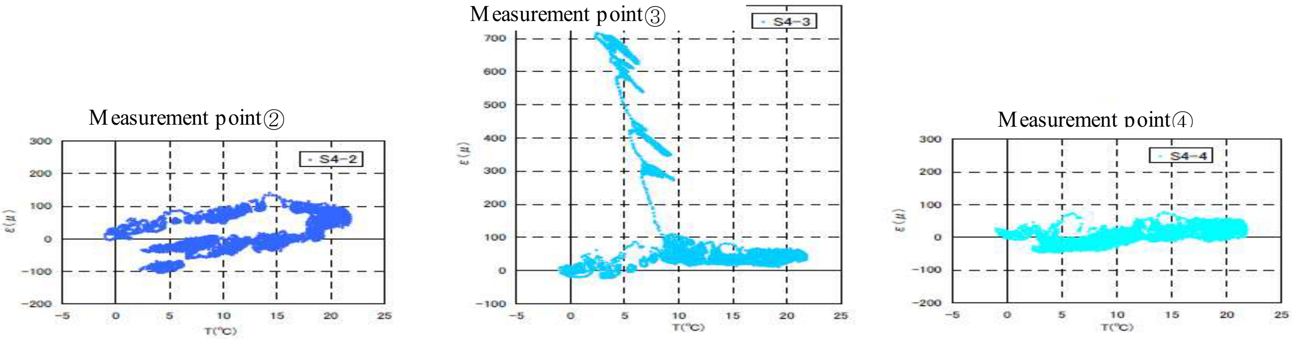


Fig. 11 Relationship between spray internal temperature and strain at measurement points ②, ③, and ④ at the secondary spray on measurement cross-section 2

greater than that for the primary spray, so it is considered that the variation in strain that occurred at the secondary spray had propagated from the primary spray.

This variation in strain at measurement point ③ is believed to have been caused by the effect of a crack that occurred near measurement point ③, as determined by subsequent visual inspection. It has been confirmed that using TDM FBG optical fiber sensing technology, it is possible to stably measure strains in the multi-layer lining, as stated above. Further, it has been found that it is possible to detect the effect of variations in the environment within the tunnel and the occurrence of cracking.

5.2 *Discussion of the measurement results*

Figure 10 shows the strain distribution relative to the strains of February 6, 2008 as the initial values, in the primary spray and the secondary spray at measurement cross-section 2 on August 13, October 13, December 1, and February 1, 2009.

Looking at the strain distribution up to October 13 and the strain distribution after October 13 in this figure, it can be seen that the variation in strain for measurement points ③ and ⑦ is different from other measurement points. Namely, from December 1 onwards the strain at measurement points ③ and ⑦ increased on the tension side. This was most prominent on the secondary spray at measurement point ③, and the amount of variation reached about 700μ in February 2009. As stated previously, this is believed to be due to the effect of a crack that occurred near measurement point ③.

Figure 11 shows the scatter diagrams for the sprayed concrete internal temperature and the strain for measurement points ②, ③, and ④ on the secondary spray at measurement cross-section 2. This figure shows a positive correlation between the internal temperature of the spray and the strain at measurement point ②. Also, looking at the strain at 5°C, it can be seen that in one year the strain varies by about 150μ on the compression side. On the other hand, looking at measurement point ④, it can be seen that it is not as sensitive to temperature variations within the spray as measurement point ②. Also, looking at measurement point ③, it can be seen that after the time that the temperature fell below 10°C the strain suddenly increased on the tension side.

From this it is considered that by monitoring the relationship between the temperature and the strain within the spray, it is possible to determine the time and location of occurrence of changes such as cracking, etc., that are caused by factors other than temperature variations.

6. Conclusion

Using this measurement method it is possible to obtain reliable long-term measurements in thin layer concrete, which is difficult using conventional electrical instruments.

Also, from the measurement results it is possible to determine the time and position of occurrence of cracking in the multi-layer sprayed lining using the multi-point measurements.

Within the measurement and monitoring area, it has been confirmed that there has been no displacement of the in-situ rock using displacement measurements of the internal void. However, it is intended to continue the measurement and monitoring in the future to evaluate the effect of repeated daily or annual variations in the air temperature within the tunnel or of seeping water on the multi-layer sprayed lining.

It is considered that the results of this construction work will help to deepen the design and construction investigations associated with the application of sprayed lining and single shell lining to other construction projects in the future.

1) Kumagai, Motoyama, Tamura, Kobayashi, Yamamoto, Moriyama: Tunnel Lining Strain Measurement using TDM FBG Optical Fiber Sensing, Proceedings of the 41st Optical Sensing Technology Research Conference, pp. 145-151, 2008.