Case Study:

Tunnel lining and tunnel shaft deformation monitoring at the Semmering Base Tunnel

Figure 1: Semmering Base Tunnel during construction (photo courtesy Austrian Federal Railways © ÖBB/Ebner)

Background

The Semmering Railway was built over 41 km of high mountains between 1848 and 1854, and is recognised by UNESCO as "one of the greatest feats of civil engineering from this pioneering phase of railway building." The 27.3 km Semmering Base Tunnel, which began construction in 2012, will relieve this legendary line of freight and most commercial rail traffic to ensure a modern and efficient transport system.

Tunnel Construction

One of the most complex building projects in Europe, the construction presents the same geological and hydrogeological challenges to today's engineers as did the original line to the designers and constructors in the mid 19th century.

The two single-track tube structure is excavated using both drill and blast, appropriately based on the New Austrian Tunnel Method (NATM) and tunnel boring.

Strain monitoring of structures

Geotechnical monitoring was used during excavation and construction to assess structural integrity and ensure safe operation.

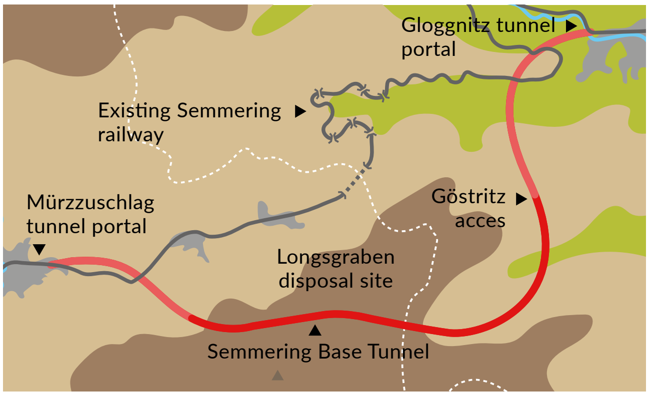


Figure 2: The routes of the Semmering line and the Semmering Base Tunnel (after Földhegy, CC BY-SA 3.0, via Wikimedia Commons).

Distributed fiber optic sensing provided displacement measurements during construction and continues to monitor the condition of:

- the tunnel and shaft linings
- a large earth retaining structure
- relocated pipelines.

The technique was used alongside point sensors (fiber Bragg gratings, vibrating wire (VWS)), and total stations.

The fiber optic system continuously monitors strain and temperature changes, detecting long-term erosion and other ground or tectonic movement. The fibrisTerre system, based on Brillouin Optical Frequency Domain Analysis (BOFDA), monitored deformation in the shotcrete tunnel and shaft linings.

Monitoring the deformation of shotcrete (sprayed concrete) tunnel lining

NATM excavation is performed in defined sequences, enabling the rock to support itself. The instrumented cross-sections were constructed in two steps. The upper part of the tunnel (top heading) is excavated and reinforced with two shotcrete layers. The lower part (bench) is removed a few days later, and the lining is completed.

Dedicated fiber optic cables, embedded during construction, enable the remote and continuous detection of strain to within a few microstrain and temperature to within 0.1°C. These sensing cables withstand pressure and vibration, making them ideal for the harsh tunnel construction environment. The interrogator unit was placed in a suitable location about 100 m from operations.

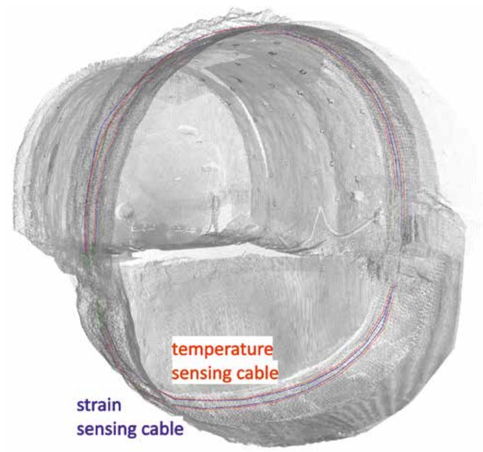


Figure 3: Position of sensing cables within the tunnel section, captured by laser scan

The sensing cables were installed on the supporting wire meshes of both shotcrete layers in a parallel formation, using cable ties. The cables' exact location was recorded using reflectorless total station measurements before the shotcrete was applied.

A novel proprietary shape sensing software provided curvature profiles, comparing the preconstruction model with actual data.

Fiber optic cable installation

Two different fiber optic sensing cables were used. The strain monitoring cable features a surface structure that bonds with the concrete all along its length and contains tight-buffered fiber. The temperature monitoring cable contains loose fibers in a gel-filled tube, preventing any strain transfer from the concrete.

Mapping the exact spatial location of both the strain and temperature monitoring cables into the tunnel's 3D coordinate system using a total station, enables cross-referencing with data from other sensors to provide continuous, reliable, and precise temperature-compensated shape sensing.

Figure 4: Shotcrete application to the top heading. Watch the video of the installation at https://youtu.be/TYML8r3Jl80

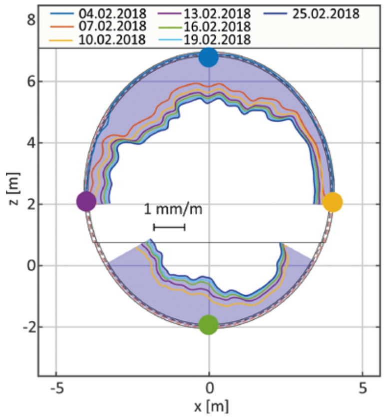
Shotcrete was sprayed following cable installation, with scanning performed before and after applying the first shotcrete layer and again following the second layer, enabling the concrete layer's thickness to be determined.

Results

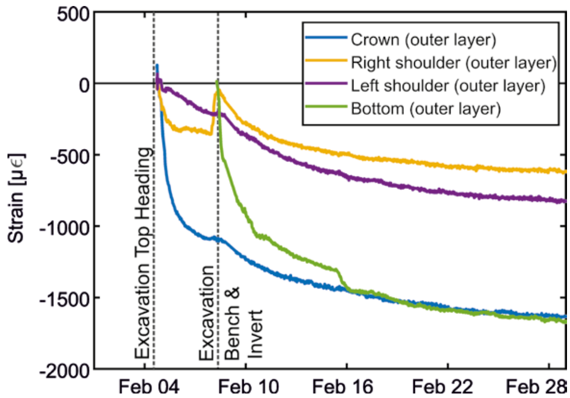
Autonomous measurements with a sampling frequency of thirty minutes began immediately after the installation of the shotcrete to monitor strain evolution, lasting several weeks, until deformation slowed, after which measurements were made monthly. The measured strain profiles (Figure 5) were all within acceptable limits.

As expected, deformation stabilizes after excavating the top heading, then increases again when the bench and invert are removed.

The strain stabilizes, as shown in Figure 6, although there is still a small amount of deformation one year later.



a. Strain distribution in the outer shotcrete layer along a tunnel cross section



b. Strain evolution in the outer shotcrete layer

Figure 5: Strain development following excavation of the top heading then the bench and invert

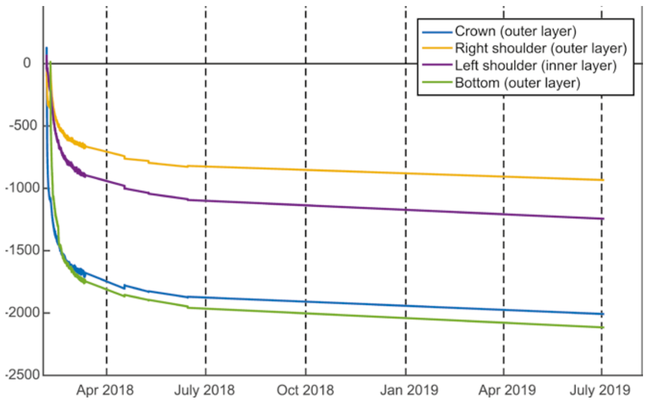


Figure 6: Long-term strain development of tunnel lining

- The distributed fiber optic measurements agreed with those from the point sensors and total stations. This data confirmed that the materials and techniques used were appropriate for this tunnel section, and construction could safely continue.

- Cross-referencing with data from other sensors provided continuous, reliable, and precise temperature-compensated shape sensing.

Shaft monitoring
A horizontal access tunnel of more than 1 km was drilled from the mountainside at Göstritz to create a large cavern. Two 240 m shafts were sunk from here, providing access to the tunnel operations below (Figure 7).

This was a challenging excavation, not only because of the complex structure, but also due to the many geological faults resulting in water ingress at several locations.

The water flow behind the shotcrete shaft lining risked eroding earth and rock.

To detect any degradation of the shafts' stability at an early stage, geotechnical monitoring was established using distributed fiber optic sensing embedded in the shotcrete linings.

Such environments are challenging for taking measurements using other technologies since:

- the steepness gave almost vertical sightings,
- the reflective survey targets quickly became dirty and were difficult to clean,
- the measurements took time and were tricky to acquire in shafts with water ingress, and
- taking the measurements physically interfered with the shaft construction and operation.

Fiber optic sensing installation
Horizontal cross-sections of the shafts at five locations between 177 and 229 m below the top cavern were selected for monitoring, based on their geology. Both layers of the shotcrete lining were instrumented with strain and temperature monitoring cables at every cross-section. These were configured as a 70 m loop, of which 35 m was strain and temperature-sensitive and 35 m measured only temperature. The position of the monitoring cables was mapped using a total station. The monitored sections were connected to a central measurement location in the top cavern, using multifiber lead cables, thus avoiding any interference with the construction process.


Figure 7: Shaft view during construction at Göstritz

Cramped conditions in the 8 m diameter shafts and the continuous water ingress down the walls made installation difficult. The instrument housing and surrounding area required waterproofing.

Measurements and results
Automatic measurements were taken once amonth to understand the shaft lining behavior, with a spatial resolution of 0.5 m and a sampling interval of 0.05 m. If significant changes were detected, the measurements switched to continuous mode.

A display of the strain results along the tunnel shaft lining provides insight into the strain evolution (zero measurement 21.08.2018 until 11.10.2018) (Figure 9).

The distribution of strain development was not even, with almost no strain occurring at the 12 o'clock position. In the three weeks following 27.08.2018 the rate of change in the strain decreases significantly more than during the following three weeks.

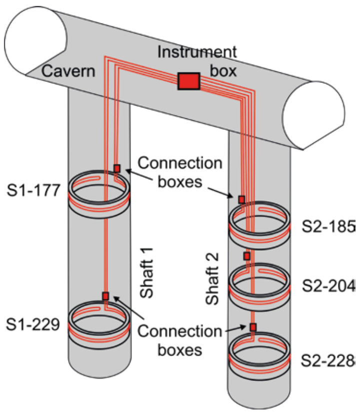


Figure 8: Distributed fiber optic measurement system at Götritz access (not to scale)

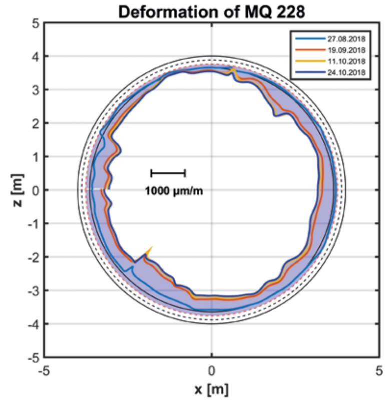


Figure 9: Strain distribution in the inner layer of the shotcrete lining (section S2-228) at different dates from the zero measurement on 21.08.2018

Measurements during the six weeks saw a maximum strain decrease of about 1000 µm/m on this cross-section.

The measurement campaign will continue until the shafts are refilled at the end of the construction, an estimated eight years, and can inform condition-based maintenance during the 150-year operational lifetime of the tunnel.

Contact fibrisTerre to discuss your project's requirements with a specialist.

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Figure 10: A fibrisTerre distributed fiber optic sensing interrogator unit

References

- Christoph M. Monsberger · Werner Lienhart
Distributed fiber optic shape sensing along shotcrete tunnel linings: Methodology, field applications, and monitoring results Journal of Civil Structural Health Monitoring
https://doi.org/10.1007/s13349-020-00455-8
- Lienhart W, Buchmayer F, Klug F and Monsberger CM
Distributed fibre-optic sensing applications at the Semmering Base Tunnel, Austria Proceedings of the Institution of Civil Engineers – Smart Infrastructure and Construction
https://doi.org/10.1680/jsmic.20.00006
- Buchmayer, F. Monsberger, C. and Lienhart, W. (2021)
Advantages of tunnel monitoring using distributed fibre optic sensing: Journal of Applied Geodesy, Vol. 15 (Issue 1), pp. 1-12. https://doi.org/10.1515/jag-2019-0065
- **Semmering Base Tunnel**
https://en.wikipedia.org/wiki/Semmering_Base_Tunnel
- **fibrisTerre fTB 5020** – Fiber-optic sensing System for distributed strain and temperature monitoring.

All diagrams and pictures courtesy of **Engineering Geodesy and Measurement Systems, Graz University of Technology**, unless otherwise noted.