International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

The Potential of Distributed Fiber-optic Sensing for Improved RRS Understanding

T. Maier & G.H. Erharter, H.J. Meland, A.K. Lund
Norwegian Geotechnical Institute, Oslo, Norway
theresa.maier@ngi.no

W. Lienhart
Institute of Engineering Geodesy and Measurement Systems, Graz University of Technology, Graz, Austria

Abstract

The Norwegian approach to tunnel support design frequently employs reinforced ribs of sprayed concrete (RRS) to mitigate adverse geological conditions such as fault zones and weak ground. However, recent studies indicate that RRS may often be mis-dimensioned, resulting in unnecessary material and cost expenditures. To address this, a recommendation of the use of various monitoring methods with consideration of the ground behavior is presented. A special focus is put on distributed fiber-optic sensing (DFOS) in support systems, which can provide insights into the interaction between tunnel support and the surrounding rock mass (i.e. the system behavior) in challenging conditions. An installation of DFOS in the Bergåstunnel marks the initial application of this technology in Norway, demonstrating its feasibility. This paper highlights the potential of geotechnical monitoring methods and especially DFOS to gain better understanding of the system behavior of RRS for different rock mass behaviors. Utilizing geotechnical monitoring can help to avoid over- or under-designed support in Norwegian tunnels and international applications of the Norwegian Method of Tunnelling.

Keywords

Norwegian method of tunnelling, Reinforced ribs of sprayed concrete, Distributed fiber-optic sensing, Monitoring, System behavior

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1 Introduction

Reinforced ribs of sprayed concrete (RRS) are a widely used tunnel support method in Scandinavia and an integral component of the Norwegian Method of Tunnelling. The basis for the design of RRS is the Q-system (NGI 2022), which provides recommendations for shotcrete thickness and number of rebars for a low Q-value, (i.e. poor rock mass). In-situ verification of the support performance of RRS through continuous measurements is uncommon.

The Q-System suggests additional design approaches, such as the observational method which can include deformation or stress measurements only in exceptionally complex areas with unfavorable rock mass conditions. As in these cases the support design has mostly changed to other support means than RRS, this paper does not focus on the determination of the actual load distribution in RRS and the occurred deformations. Most installations of RRS are without any analysis regarding capacity or support pressure (NFF 2017, Høien et al. 2019).

Grimstad et al. (2002) introduced the RRS to the Q-system based on empirical data related to the Q-value and numerical models. Several factors, including the database and software selected for the analysis by Grimstad et al. (2002), suggest that the incorporation of RRS in the Q-system was designed conservatively, without a thorough understanding of RRS's performance. RRS was designed to act as a load-bearing structure, but several studies on the performance of RRS indicate that the support system is over-dimensioned and acts more as a rock-reinforcing structure (Holmøy 2002; Grimstad et al. 2003, Mao et al. 2011, Chryssanthakis 2015, Høien et al. 2019, Terron-Almenara et al. 2024). In two cases, under-dimensioning of RRS led to a collapse of an RRS support tunnel section, demonstrating the system's weaknesses. Considering mis-dimensioning of RRS, today's geotechnical RRS design is questionable and should be revised (Høien 2024).

A tunnel design aims to find a solution that, on the one hand, is reliable and safe throughout the planned service lifetime, but on the other hand, also cost-effective and has a low environmental footprint. Given these challenges, it is essential to conduct research to better understand the system behavior (i.e., behavior resulting from the interaction between ground, excavation, and support, according to ÖGG 2014) of support elements like RRS to optimize the dimensioning. RRS has the potential to constitute a replacement for heavier support elements like cast-in-place concrete if it is possible to show that the arches achieve the same target levels of reliability. Following the internationally adopted observational method in geotechnical engineering (Peck 1969), in-situ measurements are an essential tool to assess the system behavior of the chosen support in combination with the encountered ground during construction and in the long term. The composite system's stress-strain behavior and stiffness and loading limits are of specific interest.

This article discusses geotechnical monitoring techniques and their potential to better understand the system behavior and structural properties of RRS. It should motivate the tunnelling industry to expand its knowledge of RRS, enabling more optimized construction. Due to the promising potential of distributed fiber-optic sensing (DFOS), a focus is placed on this technology. The article provides measurement recommendations for RRS to allow design optimization.

2 Background

2.1 Reinforced ribs of sprayed concrete (RRS)

RRS are structural elements consisting of steel bars embedded in shotcrete (layers with and without steel fiber) and fixed to the rock mass with bolts, T-pieces, washers, and nuts to increase strength and load-bearing capacity (NFF 2008). In Norway, the design basis of RRS (thickness and number- and spacing of ribs and the diameter of steel bars) follows the Q-system (NGI 2022). Static calculations or numerical modelling are only applied in the case of complex geometries or difficult conditions (Høien et al. 2019; NFF 2008; Statens Vegvesen 2023).

The installation of RRS is either arched or unarched. The former constitutes a load-bearing arch and requires that tunnel profile irregularities are filled with shotcrete to create a smooth profile. Compressive stress should then act on the arch. In the case of an unarched RRS, the rebars follow the blasted, rugged tunnel profile, and the arch is subjected to moments and shear forces at individual points (Pedersen et al. 2010). A Q value of <1 leads to using a double layer of rebars built similarly to single-reinforced RRS. The general assumption is that double-reinforced arches have a greater capacity to withstand both compressive stresses and bending moments (Statens Vegvesen 2023).

The use of RRS offers several advantages over other lining systems. The excavation is much faster using RRS than with cast-in-place concrete lining, as the rigging of the cast frame and concrete curing are comparatively long (Høien et al. 2019). The rebars have a uniform length and can be stored easily on-site, which enables quick and flexible use (Holmøy 2002).

2.2 Geotechnical monitoring in conventional tunnelling

Tunnel construction using the observational method (Peck 1969, NS-EN 1997-1:2004) deploys geotechnical monitoring during construction to verify the planned system behavior to ensure stability, performance, but also economic viability of the tunnel structure under different geological conditions. A geotechnical monitoring concept is developed in the design phase for the specific project requirements and boundary conditions. Monitoring concepts include several phases: i) the key geotechnical parameters and observational variables are determined in the preliminary design phase, and their expected value ranges are defined. ii) the method for measuring these parameters is developed within the conceptual design phase. iii) During the specification phase, the concept is refined into a comprehensive monitoring program that includes instrument selection, field performance, and installation procedures. iv) This is followed by the installation and data collection phase. v) Finally, in the data processing and evaluation phase, the collected data is analyzed, evaluated, and summarized in reports that serve as a basis for decisions and possible adjustments in construction (NS-EN ISO 18674-1:2015).

Various monitoring technologies are available depending on the objective of the measurements. ÖGG (2014) has determined the relation of the applicable observational method to the observational variable. Based on the variables of interest in investigating RRS, the selected monitoring methods are geodetic monitoring, extensometers, total pressure cells, strain gauges, and DFOS.

A widely used geodetic monitoring method is absolute 3D displacement monitoring. Typically, five targets are fixed to the tunnel lining per measurement cross-section, three at the top heading and the bench/invert. The distance of the targets in the longitudinal direction of the tunnels varies depending on the project and the required measurement density and accuracy. The measurements are then carried out manually with a total station at a regular time interval (often once per day). To obtain an accuracy of 1 mm for the absolute position of all coordinate components of the marked measuring points, the surveyor must follow specific conditions regarding the distance between the measuring points and the measuring process. The result of each measurement series is a 3D displacement vector (ÖGG 2014).

An extensometer records the changes in distance between two points in the direction of the measuring line. Rod and tape extensometers are applicable for tunnel excavation, and the measurement readings are mostly automated. The accuracy and resolution of the measurement depend on the extensometer type and measuring length but is usually 0.1mm (NS-EN ISO 18674-2:2016, ÖGG 2014).

Strain gauges are a method of direct strain measurement in the tunnel lining. Installation of strain gauges is usually fast and easy, and data acquisition is done automatically with an online connection to the site office. The device should have a minimum measuring range in tension of 0.2% and compression of 1%. The accuracy of the system should be higher than 1% (ÖGG 2014).

Total pressure cells measure the total normal stress change acting on the planar side of the cell. The cell can be embedded in the tunnel lining or between the ground and the lining. Pressure cells are highly temperature-dependent, and during shotcrete curing, a gap can develop at the device-shotcrete interface. Pressure cells are highly susceptible to errors as the measuring device changes the stress field, which plays an important role during the hardening of sprayed concrete. The accuracy depends on the conformity between the cell and the surrounding medium (NS-EN ISO 18674-5:2019).

2.3 Distributed fiber-optic sensing (DFOS)

DFOS is a technology that uses light backscattering in optical fibers to continuously measure physical quantities such as temperature, pressure, or strain along the entire length of the fiber. An optical transmitter, usually called interrogator, sends a light signal into the fiber, and a receiver evaluates the backscattered light, whereas various scattering principles exist. The return time of the backscattered light is used to determine the position of the deformation, and the frequency shifts of the scattered light are analyzed to obtain information about the physical conditions at the specific points along the fiber (Döring et al. 2016, Zhang et al. 2024). The resolution of strain measurement with DFOS is 1 µm/m.

The use of DFOS to conduct deformation measurements in tunnels offers several advantages: i) Continuous measurement along the entire fiber provides high-resolution information on strain and temperature, allowing the evaluation of physical conditions accurately. ii) By measuring in real-time, an immediate response to critical changes can be realized (Döring et al. 2016, Monsberger et al. 2018, Monsberger et al. 2022). iii) The cables of the DFOS system are sensors and data transfer cables in one. iv) The sensors are relatively small in size and low in weight, which facilitates the installation (Wagner et al. 2020). v) The measuring device can be placed several kilometers from the measuring location without electrical power at the sensor. vi) DFOS technology is relatively robust and resistant to environmental influences, thus increasing the measurements' reliability (López-Higuera 1998, Döring et al. 2016).

However, the DFOS system is unsuitable when yielding elements are used or when very large crack widths occur along the lining (Monsberger et al. 2021). Currently, the costs for DFOS are high compared to conventional monitoring devices. However, the development of the technology is still ongoing, so decreasing costs can be expected in the future. (Wagner et al. 2020).

In recent years, the use of DFOS to measure deformations in tunnels has been frequent. Zhang et al. (2024) provide a comprehensive summary of the developments and applications of DFOS for deformation monitoring of tunnel structures. DFOS was successfully used to monitor rock pressure and strain during the construction of various tunnel structures in Austria (Henzinger et al. 2018, Monsberger at al. 2018, Wagner et al. 2020, Monsberger et al. 2021, Monsberger et al. 2022, Monsberger et al. 2024). The results from an application of DFOS at a deep tunnel excavation show that the measured strains aligned well with the expected deformation characteristics (Henzinger et al. 2018). With a DFOS installation at a shallow tunnel construction, Monsberger et al. (2021) were able to detect the ovalization of the tunnel lining due to the applied load at terrain level.

3 DFOS Installation in Bergåstunnel

The Bergåsen road tunnel, located near Mosjøen in northern Norway, is approximately 2 km long and primarily traverses hard rock formations such as marble and granite. In December 2022, excavation encountered an unexpected 70 m soil zone consisting of a dense and ancient clay moraine overlying, weathered, disintegrated rock (Margreth et al. 2024). Starting in January 2023, the designer suggested pre-investigations and a design study to develop excavation and temporary support strategies.

The chosen approach involved using – comparatively short – excavation lengths of 1.5 -2.0 m under the protection of spiling and pipe umbrella bolts. The new excavation and support strategy included installing drainage holes in the tunnel face to mitigate pore pressure and control potential erosion, while grouted face bolts with plates were used for stabilization. Additionally, 10 cm of reinforced sprayed concrete were applied to ensure working safety near the face. The tunnel cross-section where the RRS was installed is semicircular. Inclinometers above the tunnel roof should monitor the displacements. Toward the end of the soil zone excavation, the Norwegian Public Roads Administration ordered the installation of DFOS in three RRS.

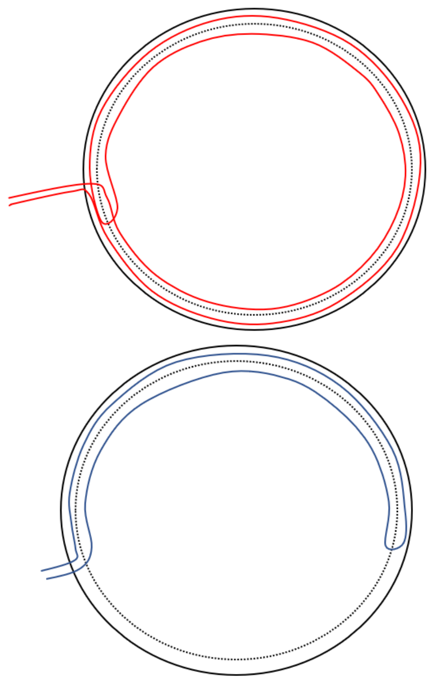

Figure 1: Schematic illustration of the DFOS setup in Arch 1. a) layout of the EpsilonSensor. b) layout of the Solifos V3 fibre optic cable.

The Distributed Fiber Optic Sensing (DFOS) installation at the Bergåsentunnelen site involved the instrumentation of three shotcrete reinforcement arches with Nerve EpsilonSensor fiber optic cables. Each arch had additional sensors to facilitate comparison and temperature compensation of data: Arch 1 included a supplementary Solifos V3 fiber optic cable (Figure 1); Arch 2 had four vibrating wire gauges positioned in the roof section for strain and temperature monitoring; and Arch 3 had a thermistor string for temperature measurements.

The installation technicians functionally tested all sensors and data loggers before installation and marked the fiber optic cables at 5-meter intervals for documentation. The starting point for the mounting of fiber optic cables was their midpoint. The workers then laid the cable along individual reinforcement bars in the arch (Figure 2). For the first two arches, the attachment of fiber optic cable to bars consists of a twisted thin steel wire, which is the same method for splicing the reinforcement bars themselves; for the third arch, the fixation of the fiber optic cable is high-quality plastic cable ties. Both methods of attachment provided good anchorage and endured the shotcrete application well. Where cables exit the arches, they were protected with cable pipes and safely routed to storage or protection cabinets for later integration.

Figure 2: Installation of the DFOS in Arch 1 at the soil zone of Bergåstunnel.

The data retrieval () utilized a Luna OBR4600 Rayleigh interrogator for fiber optics, with standalone Geokon dataloggers recording the vibrating wire and thermistor data. The workers completed the reinforcement bars installation and the exit pipe's mounting in alignment with the tunnel construction schedule and finished each arch within approximately 1-2 hours.

4 Improving RRS system behavior understanding

Determining system behavior parameters is crucial for assessing the structural performance of materials and components. Key parameters include the capacity to resist bending moments, shear forces, and compression. Understanding the loading limits is essential for ensuring safety and reliability. These parameters can be evaluated through various measurement methods, each offering unique advantages depending on the specific application.

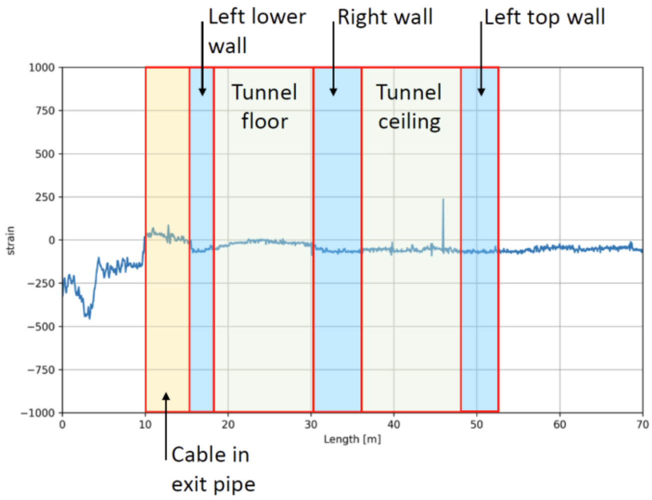

Figure 3: Example of a strain measurement result with DFOS

Table 1 provides an overview of suitable monitoring methods for gaining information on RRS performance in relation to different ground behaviors. The authors classify the ground behavior types in this example according to ÖGG (2010). Still, the translation to other classifications of ground behavior types is possible (Hoek et al. 1995, Palmstrom and Stille 2007, Terron-Almenara et al. 2024). The table does not include ground behavior types for which RRS is not used, such as 'stable,' 'rock burst,' and 'flowing ground'. The numbering of the ground behavior types in Table 1 follows ÖGG (2010).

Table 1: Proposal for geotechnical monitoring methods for the analysis of RRS system behavior under consideration of the ground behavior types 2, 3, 4, 6, 7, 8, 10 and 11, according to ÖGG (2010)

Geotechnical monitoring of RRS	*2) Potential of discontinuity-controlled block fall*	*3) Shallow failure*	*4) Voluminous stress induced failure*	*6) Buckling*	*7) Crown failure*	*8) Raveling ground*	*10) Swelling*	*11) Ground with frequently changing deformation characteristics*
3D displacements monitoring		■	■	■	■	■	■	□
Extensometer		■	■	■	■	■	■	□
Total pressure cell		■	■	■			■	□
Strain gauges			■			■	■	□
DFOS		■	■	■	■	■	■	□

Table 1 shows that RRS may be applicable for several ground behavior types but analyzing the system behavior with geotechnical monitoring may not be possible for all. Monitoring works well in cases with ongoing deformation but is futile for spontaneous failure modes that happen unannounced such as ground behavior type 2. Due to a high degree of heterogeneity, each considered monitoring technology may or may not fit to behavior type 11, which must be evaluated on a case-by-case basis. In the following, the paper discusses each measurement method covered in this paper in terms of its possible application and potential for use in RRS.

Absolute 3D displacement monitoring with targets is relatively easy to install and quick to determine the movement of the lining over time. The positioning of the targets is at a minimum of 10 mm from the inner lining surface. When installing the targets, the mounting of the target bolts should be in between and at the same time as the installation of the reinforcing bars of RRS. The result of the measurements then ideally reflects the deformations in the center of the support, whereby, in most cases, the position of the targets is closer to the inner surface of the lining. Due to the punctual positioning of the targets and manual measurement, the obtained data regarding the location and time of the displacement is not continuous. The absolute 3D displacement measurement can help to gain information about the system behavior in an environment where the displacements over the cross section are rather continuous than punctual (ÖGG 2014).

In tunneling, extensometers help to determine the axial displacements in boreholes. The aim is to identify the depth and magnitude of the displacements around the excavation. This information is essential for deep excavations where a high-stress state leads to plastic deformation. Another application of extensometers in tunneling is to determine shearing along faults. In general, installing the extensometer's head paired with a 3D displacement target is recommended for a comprehensive analysis of the measurement results (ÖGG 2014). The installation of an extensometer at RRS should be simultaneous with the rock bolt installation. In the past, convergence measurements have been conducted with tape extensometer to control the performance of RRS in a sub-sea tunnel (Holmøy 2002).

When placing strain gauges in RRS, it is helpful to install them in pairs, one on the inner side and one on the outer side of the lining. With this setup, sectional forces and bending moments could be calculated using the relationships from NS-EN 1997-1:2004. As the results provide information about the excavation cross-section at specific points, the technology suits conditions where a uniform load will most likely act on the arch across the entire cross-section.

Another method to gain direct information about the strain in the lining is to install DFOS. The sensing cables are directly embedded in the shotcrete or attached to the rebars of the RRS. Thus, the installation can either be closer to the outer side of the lining or toward the inner side, providing a wide variety of information about the system. The reading of the results is automatic and continuous. With the continuous strain distribution results across the entire cross-section, this method can provide information about the behavior of RRS when subjected to variable loads according to the cross-section. Due to the high resolution of strain measurements, DFOS can deliver better results when small deformations are present. As in the past, other monitoring methods have failed to detect the relatively small deformations occurring when installing the RRS, DFOS could provide information on a more precise scale (Grimstad 2003, Høien 2019).

Total pressure cells (TPC) can provide information about the radial or tangential stress in the RRS lining and shotcrete-rock-contact stress, depending on the positioning of the cell pad. The rebars of the RRS can serve as the fixing point of the cell. The measurement results are collected automatically and give information about the stress state in the specific location of the cell pad. TPC does have the potential to provide valuable data in case of perfectly arched RRS and when large deformations occur (Høien and Nilsen 2018). However, due to undulations or depressions in the ribs and very low load, it was impossible to retrieve reliable data from TPC measurements in RRS (Grimstad 2008).

5 Conclusion and Outlook

This paper addresses the knowledge gap about RRS system behavior and geotechnical monitoring of installed RRS is proposed as a measure to close this gap. The success of obtaining reliable measurement data lies in selecting the appropriate technology in consideration of the ground behavior.

A particular focus lies in applying strain measurements with distributed fiber-optic sensing. DFOS technology enables precise strain monitoring from the moment of installation through the entire lifecycle of the tunnel, capturing both short-term behaviors during excavation and long-term performance during operation. The knowledge gained enhances understanding of current support measures and provides a robust decision basis for optimizing tunnel linings. The example Bergåstunnel presents a successful application in Norway.

DFOS monitoring is therefore well suited for helping in challenging tunnelling conditions where current Norwegian practices, such as the Q-system, find their limits. By leveraging DFOS, we can move towards more efficient and cost-effective support designs in challenging conditions, potentially helping to avoid over-engineering.

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