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APPLICATION OF REINFORCED RIBS OF SPRAYED CONCRETE (RRS) IN THE NEW AUSTRIAN TUNNELING METHOD (NATM)

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ABSTRACT

Tunnel design approaches in Austria and Norway differ significantly due to their underlying methodologies. In Austria, the New Austrian Tunneling Method (NATM) is used to determine lining systems on a project-specific basis. In contrast, the Norwegian Method of Tunneling (NMT) in Norway relies on the Q-system, where support selection is directly tied to rock mass classification. For a low Q-value, which indicates poor rock conditions, the rock support system suggested by the Q-chart is Reinforced Ribs of Sprayed Concrete (RRS). RRS offers several advantages in practical applications, yet research on the system remains limited, and mis-dimensioning of RRS in the Q-chart is suspected. This study aims to analyze the RRS lining system in detail based on convergence measurement data from the Frøyatunnel in Norway and explore its potential integration within the NATM. First, analytical calculations using the Confinement Convergence Method (CCM) are conducted. Then, numerical modeling with RS2 software is performed to simulate the system's behavior. Finally, structural design calculations are carried out. The results show that the calculations yield consistent results, though these analyses require simplifications that introduce limitations. The methods used cannot adequately determine the mechanical behavior or load limit required for NATM. Therefore, the author sees RRS with the current state of knowledge as inadequate for use within the NATM. However, using RRS could bring many advantages to the NATM, so future research should focus on better understanding its behavior.

Keywords: Reinforced Ribs of Sprayed Concrete, Q-System, Norwegian Method of Tunneling, New Austrian Tunneling Method, rock tunneling

INTRODUCTION

The Norwegian Method of Tunneling (NMT) includes using Reinforced Ribs of Sprayed Concrete (RRS) in tunneling projects across Scandinavian countries as a structural support element. Within the NMT, engineers use the Q-system, an empirical rock mass classification method, to guide the decision-making process for the RRS design (NGI, 2002). The decision outcome includes determining key parameters such as rib thickness, the number and spacing of bars, number of layers of steel bars, and the diameter of steel bars. Figure 1 and Figure 2 illustrate the components of RRS.

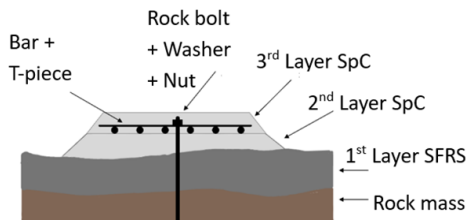


Figure 1 Schematic cross-section of the installation of the RRS single layer with 6 bars. SpC = Sprayed concrete, SFRS = Steel fiber reinforced shotcrete

Grimstad et al. (2002) suggested the design of RRS and implementation in the Q-chart. The design is on the conservative side, based on empirical data calibrated with numerical analysis and deformation measurements. Research findings indicate that the support pressure from RRS is rarely activated, as intended, despite its design as a load-bearing structure (Grimstad et al., 2003; Mao et al., 2011; Chryssanthakis, 2015; Høyen, 2019). Instead, RRS stabilizes loose rock blocks rather than contributing significantly to structural support. Høyen (2024) argued that the approach by Grimstad et al. (2002) for implementing RRS in the Q-chart is inadequate for a proper design of the RRS. These arguments raise concerns about mis-dimensioning, leading to unclear safety, unnecessary material use, increased costs, and higher CO₂ emissions.



Figure 2 The arrangement of the bars before application of the covering layer of sprayed concrete. T-pieces used to create an arch

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The New Austrian Tunneling Method (NATM) is an observational approach that requires a thorough understanding of the system's mechanical behavior (ÖGG, 2021). The performance of RRS is evaluated to assess its potential implementation within NATM using available engineering tools and the current state of knowledge.

The analysis is conducted using the Confinement Convergence Method (CCM), numerical modeling, and structural design calculations. Using data from the Frøyatunnel, the aim is to provide a clearer understanding of RRS performance and guide the development of more cost-effective and sustainable design solutions.

The basis of this paper is the research conducted in the author's Master's thesis at Montanuniversität Leoben. (Maier, 2023)

FRØYATUNNEL

The data for this analysis originates from the Frøyatunnel, part of the mainland connection between Frøya and Hitra, two islands located northwest of Trondheim, Norway. The tunnel is a single-tube road tunnel, measuring 5.3 km in length, with a height of 4.5 m and a width of 6.5 m. A significant portion, 3.8 km, is a sub-sea tunnel (Frøyatunnelen Ingeniørgeologisk Rapport, 1999, unpublished). The tunnel's alignment primarily passes through Precambrian gneissic rocks that have undergone significant metamorphism, with multiple fault zones cutting across the formation.

The rock type at chainage 6+495 is a migmatic gneiss. The RQD was determined as 17, J_r as 15, J_f as 1, J_s as 8, J_w as 1, and SRF as 5. These values result in a Q-value of 0.02.

The rock support design follows the Q-system. Data was taken from chainage 6+495 of the Frøyatunnel for the analysis. This position was selected based on promising convergence measurement results, the presence of geological conditions with a low Q-value, and the implementation of RRS as the support system.

The RRS studied in this paper consists of one layer of 6 rebars with a rebar diameter is 16mm and a rebar spacing of 0.1 m. The spacing between the RRS arches is 1.5 m and the RRS width is 0.7 m. The smoothing layer of shotcrete is 0.23 m and the shotcrete covering layer is 0.12 m.

CONFINEMENT CONVERGENCE METHOD

The CCM is a simplified two-dimensional analysis that describes the three-dimensional behavior of an underground opening, focusing on the interaction between the ground and the support. The analytical calculations of the CCM follow the approach outlined by Panet and Sulem (2022). The Generalized Hoek-Brown criterion with plastic behavior is the assumed failure criterion for the Ground Reaction Curve (GRC).

The Support Characteristic Curve (SCC) combines the composition of shotcrete, reinforcement and bolts. The shotcrete is considered a circular ring with a constant thickness. Hoek (1998) presents formulas for incorporating various steel sets in the SCC. No formula is available for rebars such as RRS. Hence, a solution for a steel set with similar assumed properties was chosen for the analysis. The bolts applied in the RRS are fully grouted bolts. However, end-anchored bolts have been selected to simplify the inclusion in the SCC.

The Longitudinal Displacement Profile (LDP) provides a detailed analysis of the radial displacement along the tunnel alignment.

NUMERICAL MODELING

The numerical modeling software for this study is RS2 by Rocscience. In-situ stress conditions were determined based on rock overburden and water pressure, utilizing information from an unpublished NGI report dated 1998. To simulate the RRS support structure in a two-dimensional model, the reinforcement bars and the shotcrete thickness were redistributed over a unit length of 1 meter in the out-of-plane direction. Consequently, the RRS is a continuous liner along the longitudinal direction of the tunnel, following the methodology outlined by Høien and Nilsen (2019) and NGI (2018, unpublished). The RS2 model results indicate a total convergence of approximately 41 mm (Figure 3).

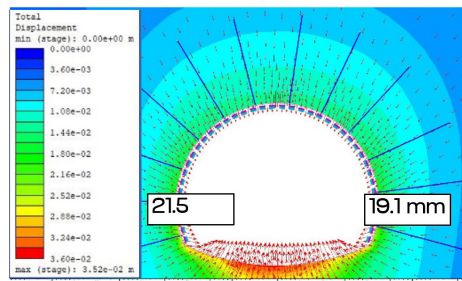


Figure 3 Total displacements in RS2 model of the Frøyatunnel at position 6+495.

To validate the RS2 model, its results were compared with convergence measurements and analytical calculations using the CCM. The measured convergence at the selected location was approximately 11 mm. Displacements ahead of the tunnel face, determined using the LDP, amounted to 6.5 mm, corresponding to a convergence of 13 mm. Holmøy and Aagaard (2002) suggest that an additional 10–15 mm of unrecorded convergence likely occurred between the tunnel face passing the measurement point and the first recorded reading. At chainage 6+495, 21 days elapsed between blasting and the initial measurement, leading to an assumed deformation of 14 mm ahead of the face. Based on these considerations, the estimated final deformation at this location is approximately 38 mm.

STATIC CALCULATION

The shear force resistance and moment capacity were determined to evaluate the structural performance and assess their alignment with the results of the CCM and numerical analysis. All calculations follow Eurocode 2. The calculated design value for shear force resistance is 120.6 kN, and the calculated moment capacity is 114.1 kN.

DISCUSSION

Comparing the shear forces and moments acting on the RRS from the numerical model and the static calculation indicates that the RRS can safely withstand the applied loads at chainage 6+495 in the Frøyatunnel, with a safety factor of 1.5 for shear force and 1.9 for moment capacity. The results suggest no overloading within the RRS support system appears under the given conditions.

The analysis included several simplifications relevant to the potential implementation of RRS in the NATM. The following section discusses the impact of the simplifications.

In the analysis, shotcrete was considered without including steel fibers due to difficulties when considering fibers. While RS2 offers an approach for modeling steel fiber-reinforced shotcrete, it was decided not to include this in the model to maintain similarity with the other analysis methods. Steel fibers enhance the energy absorption capacity, fatigue and impact resistance, and long-term crack control of shotcrete (Höfler et al., 2012). Therefore, the composite RRS in this study may be able to absorb more energy than was accounted for.

The displacement results from the CCM align with the research conducted by Terron-Almenara et al. (2023), who performed a similar analysis under comparable conditions. Significant differences in the mobilized support pressure are likely due to the use of different steel sets as input in the analysis. These variations highlight the importance of consistency in input parameters for accurate modeling. A significant limitation of the CCM analysis in this study is the assumption that all components are installed simultaneously, which does not reflect the actual construction process. Additionally, while the calculation considers end-anchored bolts, the actual system uses fully grouted bolts. This distinction is important as the stabilization modes differ. An end-anchored bolt provides support, whereas a fully grouted bolt is seen as a reinforcement of the ground, affecting the system's overall performance.

The results from the numerical model indicate the formation of a perfect arch, which typically does not occur in real-world conditions. In the model, no extreme shear forces and moments appear on the support, which disregards potential occurrences in a tunnel. The smearing out of the RRS in the RS2 model is also questionable. From the author's perspective, redistributing the reinforcement

over a unit length may not be appropriate, as the equivalent support does not have the same material properties as the actual system. There is a lack of literature supporting this approach.

The ÖGG (2021) guideline for conventional excavation in Austria requires specifying the utilization of supporting elements. Thus, to use RRS in the NATM, the load capacity, deformation limits, failure points, maximum support pressure, and system stiffness of the support system must be known. A comparison of the information required for NATM and the available information regarding the mechanical behavior of RRS reveals significant gaps. Numerous assumptions were necessary for analysis, but their impact on result reliability remains uncertain due to limited data. This study shows that the current understanding of RRS behavior is insufficient for its application in NATM.

However, RRS could offer a valuable addition to the NATM, as its bars don't require prefabrication or welding, like other support means. It provides a quick and cost-effective backup solution for unexpected changes in rock conditions.

Future research should focus on implementing continuous measurements, enabling more accurate validation of theoretical models. Developing a verified solution for considering ribs within the SCC will enhance the system's modeling. Further, the plausibility of modeling the RRS in RS2 using equivalent support redistribution should be verified through comparison with experimental data. Finally, 3D modeling of the system would provide a more comprehensive understanding of the interactions between the support and surrounding rock mass, leading to more accurate predictions of the system's behavior.

CONCLUSION

The study results show that the RRS support system in the Frøyatunnel is not subjected to overloading. The loading limit for the RRS could not be determined in this study and should be explored in future research. The analysis highlights that the current understanding of the mechanical behavior of RRS is limited, with design and implementation primarily based on empirical data, which, coupled with the scarcity of measurement data, necessitates several assumptions during analysis. Therefore, the use of RRS in the NATM is not recommended according to the current state of knowledge. While RRS may perform well within NMT due to system over-dimensioning, further research is essential for its application in NATM.

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LABORATORY TESTING AND EXPERIMENTAL RESULTS

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