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Design of reinforced shotcrete arches in rock tunneling projects

A literature and case study that aims to illustrate the complexity of designing reinforced steel rebar shotcrete arches

Master's thesis in Infrastructure and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Steel reinforced shotcrete arches constructed in the West link project at a service tunnel close to the Korsvägen station (photo taken by the author).

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Analysis of the design process of shotcrete arches in tunneling projects
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Abstract

Reinforced steel rebar shotcrete arches are a support measure that is commonly used where poor rock conditions prevail, such as thin rock coverage and fault zones. Further, technical challenging projects with for example wide tunnel spans, for example in the West link project, can justify the use of these arch solutions. However, as of right now in Sweden, there are no clear requirements or recommendation on how to properly design these arches. There are also no clear separation between when the arch are interacting with the rock mass and when it can be considered a stand alone steel concrete construction. This causes confusion in the designing phase since it is not clear if a rock mechanical or a structural engineer should be assigned to the problem. It is also not clear which requirement documentation, such as "Projektering av bergkonstruktioner", TRVINFRA-00233 and Eurocode, that are applicable. This thesis aims to illustrate these problems and to provide more documentation and knowledge on the subject. A more clear design process of reinforced steel rebar shotcrete arches would likely simplify the designing phase for the engineers. It would also benefit the developer since it would be easier to control constructed arches against the drawings and tolerances.

To solve the mentioned problems this thesis has conducted a literature and case study review on the topic. The literature review gathers information on the decision making and design process of support measures in general but focuses on reinforced steel rebar shotcrete arches specifically. The case study review covers cases in Sweden that have designed and constructed reinforced steel rebar arches. The combined knowledge gained by conducting a extensive literature review, case study review and consulting experts on the subject has shown that the national requirements and recommendation regarding reinforced shotcrete arches are limited. There are also no clear distinction whether the arch interacts with the rock mass, making it hard to consider the arch as a stand alone structure where Eurocode is applicable. It is suggested that the available requirements and recommendation documents in Sweden are further developed regarding reinforced shotcrete arches. It is also suggested that the presence of rock bolts could define if the arches are interacting with the rock mass which would make it clear what design approach that could be used.

Keywords: reinforced steel rebar shotcrete arches, support measures, tunneling, design process, requirements.

Acknowledgements

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I would like to thank Norconsult AB for providing me with a office space to conduct my thesis. Also a big thanks to the employees for input, suggestions and ideas when needed.

Thanks to representatives at the Swedish Transport Administration for providing the author with information and drawings of the West link project and E4 Stockholm Bypass project, and for a interesting study visit at the Korsvägen station on the West link project.

Lastly, due to an unfortunate event where the author suffered a concussion early in this project, which lead to the author missing at least 200 working hours, I would like to deeply thank everyone involved for understanding and supporting me through this tough time. This outcome would sincerely never have been possible without it.

Simon Marklund, Gothenburg, June 2022

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Introduction

One of the world's first tunnels was constructed in the mid 6th century BC (Akis & Satici, 2017; Hoek, 2008). It was built in the Samos islands of Greece and had the purpose to provide the city of Samos with water. The tunnel is known as the Eupalinus tunnel, named after the responsible engineer Eupalinus of Megara who also is one of the first engineers whose name is known. The tunnel was almost 1000 meter long and was excavated from both sides of the hill. The intersection where offset with less than 5 m. It was not perfect but was still considered one of the greatest engineering achievement at the time (Sandström, 1963). The tunnel where rediscovered in the 1882 and are currently undergoing restorations and maintenance (Papantonopoulos, 2022).

Figure 1.1: *Photo showing the Eupalinus tunnel, constructed around the year 500 BC, located at the Samos islands in Greece (Wikimedia common, 2013).*

In modern days, cities are expanding and central real estate prices are consistently rising. Therefore, the incentive to utilized tunnels to relocate certain activities underground are increasing. For example in Gothenburg Sweden, a major project called the West link project is currently being constructed. This project will benefit the connections to the city center without taking up valuable space at ground level (Lindblom, 2018; Swedish Transport Administration, 2021c). The same is possible for various facilities such as parking, archives, waste water treatment, etc. It is likely that underground constructions will be used even more often in the future when real estate prices are rising and it gets more and more economically feasible to put some facilities underground (Lindblom, 2018).

1.1 Background

Design can according to Cambridge English dictionary be defined as "a drawing or a set of drawings showing how a building or product is to be made and how it will work and look". Further, *process* is defined as "a series of actions that you can take in order to achieve a result" (Cambridge English Dictionary, 2022). These words are commonly used in the construction industry, both separately and together. It is generally important to asses and analyse both the design and processes used. It is often possible to improve and modernise the design and streamline the process.

Depending on the ground conditions, underground constructions often need some type of support measures either permanently and/or temporarily (Barton et al., 1974). There are several different temporarily support measures that aim to ensure a safe excavation and retain the cross section. These support measures can for example be shotcrete, grouting, bolting and spiling. Further, there are also support measures that aim to permanently support the stability of the excavation. These could be point support as rock bolting to secure blocks from falling and also surface support as shotcrete.

According to the Norwegian Geotechnical Institute (2015) the use of shotcrete has steadily increased with the heightened requirement for safety. Further, the increased accessibility to alkali free accelerators economically and environmentally benefits the use of shotcrete (Norwegian Tunneling Society, 2010). Shotcrete can be used as a support measure to protect the surface of the tunnel profile, both sporadically and uniformly. Further uses of shotcrete can also be protection against corrosion of steel reinforcements and water proofing.

Steel reinforcement can be added when traditional support measures are not sufficient. This is often the case in low quality rock, in situations with thin rock coverage and/or in tunnel constructions with high stresses. The steel reinforcements can take several different shapes and sizes as surface support and can be referred to as for example rebars, mesh, ribs, vaults, grids and lattice girders (Norwegian Tunneling Society, 2010). *The term reinforced shotcrete arches is in this study refers to the steel rebar option since these are currently being used in underground constructions in Sweden.* Reinforced shotcrete arches are, in short, constructed by attaching steel reinforcement on the tunnel profile and then covering it with shotcrete (Carranza-Torres & Diederichs, 2009). As mentioned the definitions of a ground support are quite widely varied. It ranges from simple reinforcement grids along the tunnel profile to more advanced steel structures with the form of arches. In all cases, shotcrete is used for surface stability, to protect the steel and to counteract water intrusion.

In Sweden, where bad rock mass conditions prevail such as thin rock coverage and/or poor rock conditions, reinforced steel rebar shotcrete arches can be implemented (Bergman & Andersson, 2019; Perman & Edelbro, 2019). However, the current documentation with requirements and recommendation is limited. The available international documents, such as Eurocode, are not intended for underground construction and the national ones only briefly cover the design of such arches. Therefore, there is no clear way of designing these arches as of today (Athanasopoulou et al., 2019).

This thesis consists of 7 chapters where chapter 2 describes the methods used to conduct the different parts of the thesis. Chapter 3 is a extensive literature review that covers the basic knowledge of designing ground supports and rock reinforcements. Further, the literature review also puts this thesis into context. In chapter 4 an in depth description of the design process of reinforced shotcrete arches is presented, both from a rock mechanical perspective and a structural perspective. Chapter 5 is a case study that covers different construction projects that have used reinforced shotcrete arches. The knowledge gained form studying these cases is the main results of this thesis. Chapter 6 presents the discussion where the knowledge gained is discussed and interpreted. Chapter 7 is where the conclusions from the results and discussion are drawn and future studies are suggested.

1.2 Problem description

The design of shotcrete arches can according to Lindfors et al. (2019) be conducted both as free bearing structure without rock interaction or as a structure that does interact with the rock mass. If it does not interact with the rock mass it could be considered a stand alone steel concrete structure and could therefore theoretically be designed by a structural engineer. Otherwise, rock mechanical engineers would likely be most suitable as designer. This is the case in the West link and E4 Stockholm bypass projects, which is further covered in this thesis. Engineers from these two fields likely approach the problem differently. Rock mechanical engineers use empirical, analytical and numerical methods to link the expected rock mass behaviour to the appropriate support (Lindfors et al., 2019). Structural engineers could theoretically separate the load, ignoring the rock mass behaviour, and design the arch as a pure concrete steel structure. If the reinforced shotcrete arch is considered to interact with the rock mass the designer must rely on national requirements and recommendations, such as "Projektering av Bergkonstruktioner" and "TRVINFRA-00233". This is because international documents, such as versions of Eurocode, are not intended for underground constructions (Athanasopoulou et al., 2019). However, the national requirements and recommendations in Sweden are somewhat limited regarding reinforced shotcrete arches. If it would be possible to distinguish if the reinforced shotcrete arches are interacting with the rock mass it would also be possible to apply the suitable supportive documentation. As stated by Lindfors et al. (2019) Eurocode is mainly applicable if it is possible to separate the load (e.g from the rock) and the bearing capacity (e.g for the shotcrete arch). Thus it requires some way to distinguish if the structure will interact with the rock mass or not. However, this seems to not be simple to determine. It is clear that some clarifications are needed regarding the design process of reinforced shotcrete arches.

When the desing process of shotcrete arches are unclear it might force the engineer to use large safety factors. This can sometimes lead to overdimensioning and uneccesary use of some the support construction (Høien et al., 2019). The use of shotcrete is efficient as a support measure. However, excessive use of shotcrete, or any material in general, is not environmentally friendly. Therefore, it is ecologically important that the design process is as optimal as possible to reduce the impact on the environment.

1.3 Aim

The aim of this thesis is to gather and compile available information and knowledge on designing reinforced steel shotcrete arches. This is conducted with literature reviews, case studies and consulting of experts. The hypotheses is that it will be possible to illustrate both the complexity of designing these arches and that the proper documentation and requirements are lacking. By doing this it might be possible to pinpoint room for improvements in the design process. Hopefully, with the knowledge gained in this thesis, it will be possible to propose an improved design process that takes a step forward against being user friendly and efficient.

1.3.1 Research questions

This study aims to answer the following research questions:

1. Is there room for improvements in the design process of reinforced steel rebar shotcrete arches?

2. Is it possible to suggest improvements to the design process of reinforced shotcrete arches?

1.3.2 Limitations

The study is delimited to cover the design process of reinforced shotcrete arches used in tunneling projects in rock. It will cover a wide variety of arches that contain some type of steel reinforcements along the tunnel profile, e.g ribs, vaults, grids and lattice girders. However, the focus point of this study are the reinforced steel rebar option since it, as shown in (Bergman & Andersson, 2019; Jonsson & Andersson, 2020; Perman & Edelbro, 2019; Radoncic, 2016), are currently being used in tunneling projects in Sweden today. Also, the shotcrete used to confine and protect the steel is not limited to any specific recipe. Hence, all common shotcrete recipes and forms of reinforcements should be able to fit into the improved design process.

2

Methods

The general method used in this study is somewhat inspired by the study conducted by Bieniawski (1973). This is possible due to the various similarities between the studies. Bieniawski (1973) aimed to suggest a new improved method for rock classification. This was done by extensive information gathering of the current methods at the time. With the information gathered it was possible to suggest a new classification method which held the benefits of the outdated ones and excluded the disadvantages.

With Bieniawski (1973) as inspiration, this study conducts an extensive and thorough literature and case study. The purpose is to map and understand how the design process of shotcrete arches is conducted at present. The aim is to understand and thereafter pinpoint both benefits and disadvantages. The final goal is to be able to suggest improvements to the design process of reinforced shotcrete arches.

2.1 Literature review

The literature review is conducted by researching relevant reports, articles and construction acts regarding reinforced shotcrete arches in rock tunnel projects. The purpose of the literature review is to gain an overview of the different aspects of the design process of such arches. This is achieved by assembling knowledge about rock mass classification, shotcrete components, different support alternatives and design methodology of both rock mechanical and structural engineers. The overall level of difficulty of the presented information in this thesis is set so that students at university level can understand and so that the information can be useful for moderate to expert readers on the subject. The studied literature is retrieved from search engines as scopus and google. Also some of the literature are provided by the supervisors of this project and experts in the industry.

2.2 Case study

The conducted case studies covers relevant projects where tunnels are constructed in rock and where advanced support measures, such as reinforced shotcrete arches, have been required. The case study covers both reinforced shotcrete arches as part of the general support and as custom support in local conditions. The case study examines the decision making process, regarding the design, in these projects and tries to illustrate why the specific support measure is chosen. Also, advantages and disadvantages of the chosen design methodology are examined to find potential room for improvements or something to learn from. The information gathering for the case study is performed by studying relevant construction acts that where documented before and during these projects. These documents where mainly provided by the developer which where the Swedish Transportation Administration.

2.3 Terminology

Since reinforced shotcrete arches are a relatively new and rare support measure in Sweden where only two reported cases, the West link and E4 Stockholm bypass project, have been found there seems to be fluctuating terminology regarding these arches. When suggesting a new way of doing something it is important that the terminology used is understandable and preferably widely acceptable. Since this study aims to suggest improvements to the design process of reinforced shotcrete arches it is important that the technical language is understandable for both geotechnical and structural engineers. Therefore, one subobjective of the literature study was to illustrate and sort out the commonly used terminology. This was conducted by listing all synonyms that showed up in literature, both in Swedish and English. Thereafter, a collective term that includes all the synonyms could be defined.

2.4 Purpose and requirements of shotcrete arches

To understand the benefits and disadvantages of different design processes of shotcrete arches one must understand the purpose and requirements of building these in the first place. Thus, answering the questions: Why are shotcrete arches being built? and For which circumstances are shotcrete arches suitable? This study answers these questions by listing both the common purposes and requirements that are linked to shotcrete arches. By clearly defining these aspects it will enable the possibility to pinpoint aspects of the design process that do not meet the requirements and intended purpose. Further, it will illustrate which requirements are relevant and potentially irrelevant in modern tunneling projects.

2.5 Comparison of different design processes

Regarding reinforced shotcrete arches in Sweden there seems to be two ways of approaching the design of these. The rock mechanical principle and the structural engineering principal. This thesis examines and compare these different design approaches to pinpoint relevant benefits and disadvantages. Further, the supportive documentation of these approaches, such as Eurocode, "Projektering av Bergkonstruktioner" and TRVINFRA-00233 are examined to illustrate the application of these in each design approach. The rock mechanical approach have been used both in the West link and E4 Stockholm bypass project, thus the documentation of this approach is quite extensive. However, the structural design approach where has only been found to be used in early stages of the West link project and only in minor parts. Thus, the discussion and conclusion regarding the structural design principle is somewhat theoretical.

2.6 Figures

Some of the figures used in this thesis are created by the author. The figures are created in Microsoft Powerpoint and Inkscape software and aims to visualise some of the processes and techniques that are discussed. The goal is to simplify for the reader and make it easier to understand some of the concepts and variety of support measures. The figures are strictly for understanding purposes and should not be used as an fully accurate representations of the concepts. However, they serves their purpose as schematic visualisations.

2.7 Study visit

A study visit where conducted on 30th of Mars 2022 at Korsvägen station on the West link project. It served as an opportunity for the author to get more close up understanding of large scale tunneling projects. Also, some of the photographs used in the thesis where taken by the author at this occasion.

3

Ground support and rock reinforcements

The chapter 3 in this study is a literature review that covers different aspects of the construction and design process of tunnels. The goal is to gather relevant information on the topic that simplifies and deepens the understanding of the reader. This literature review contains general information of support measures, concrete components and rock mass classification. Further, a more in-depth review of shotcrete, reinforced steel rebar arches and the design process of these are also included.

3.1 Rock mass classification

Preinvestigation in underground construction projects is essential to ensure an as accurate as possible mapping of the rock mass. Extensive preinvestigation reduces the risk of unforeseen rock conditions that might complicate and prolong the construction process. Historically there has been several collapses of tunnel faces, often where the rock mass quality has been very poor (Norwegian Tunneling Society, 2010). These so-called fault zones are often the most challenging and critical part of the construction of tunnels. Without sufficient information of the rock mass the chosen support measures may not be adequate. This could lead to the rock support failing and the tunnel collapsing. This is of course costly and time consuming but most importantly it is not safe as a workplace. Therefore, a thorough classification of the rock mass is essential in tunneling projects.

Four common methods to determine the rock classification are covered in section 4.1.2-4.1.5 below.

3.1.1 Q-system

The Q-system as first presented by Barton et al. (1974) and has since then been commonly used to determine the rock mass quality. The Q-system consists of 6 parameters that need to be estimated, see below. These parameters make up the equation that can be used to calculate the Q value. The Q-value is empirically linked to certain support measures. Hence, a certain Q value gives an indication of which type and quantity of support measure that are required (Norwegian Geotechnical Institute, 2015).

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \tag{3.1}$$

where:

RQD = Degree of jointing
Jn = Joint set number
Jr = Joint roughness number
Ja = Joint alteration number
Jw = Joint water reduction factor
SRF = Stress reduction factor

3.1.2 Rock Mass Rating

Rock mass rating was firstly introduce by Bieniawski (1973) and has since then received several updates. RMR was created by combining the classification methods that were available at the time. This made it possible to benefit from each of their positive aspects and compensate for their disadvantages.

$$RMR = R1 + R2 + R3 + R4 + R5 + R6 \tag{3.2}$$

where:

$R1$ = Intact rock strength
$R2$ = RQD
$R3$ = Discontinuity spacing
$R4$ = Joint condition
$R5$ = Groundwater
$R6$ = Joint orientation

3.1.3 Hoek and Brown, Geological Strength Index GSI

The geological strength index (GSI) was firstly introduced by Hoek (1994) and Hoek et al. (1995) and has since then been modified and adjusted several times. GSI is a rock mass classification that uses tabular rating of surface conditions and structure of the rock mass. High GSI values indicate good rock mass quality and vice versa. With the established GSI value, parameters needed for the Hoek-Brown failure criterion can be calculated, see equation 3.3 to 3.5, (Hoek & Brown, 2019).

$$m_b = m_i * exp[(GSI - 100)/(28 - 14D)] \tag{3.3}$$

$$s = exp[(GSI - 100)/(9 - 3D)] \tag{3.4}$$

$$a = 1/2 + 1/6(e^{-GSI/15} - e^{-20/3}) \tag{3.5}$$

Where:

GSI = Geological strength index
m_b = Hoek-Brown constant m
m_i = Hoek-Brown constant m for the intact rock
D = Degree of disturbance
s and a = Constants depending on the characteristics of the rock mass

These material parameters can thereafter according to Hoek and Brown (1997) be used in the Hoek-Brown failure criterion for jointed rock masses, see equation 3.6.

$$\sigma_1^{'} = \sigma_3^{'} + \sigma_{ci} \left(m_b \frac{\sigma_3^{'}}{\sigma_{ci}} + s \right)^a \tag{3.6}$$

Where:

$\sigma_1^{'}$ = Maximum effective stresses at failure
$\sigma_3^{'}$ = Minimum effective stresses at failure
σ_{ci} = uniaxial compressive strength of the intact rock pieces

3.1.4 Measurements while drilling

According to van Eldert et al. (2020) measurements while drilling or MWD are a efficient way of complementing the preinvestigation and mapping of the rock mass. Since site investigations, especially in rock, can be quite inaccurate and leave a large range of uncertainties, additional measurements ahead of the tunnel face could be beneficial. In that case new information on what lays ahead are progressively being gathered. This significantly reduces the risk of blindly encountering fault zones that could cause significant problems. For example, Norwegian Tunneling Society (2010) describes several cases where tunnels have collapsed due to fault zones of very poor or almost soil like rock quality. These cases could potentially be avoided or minimised with the use of MWD.

3.2 Support measures

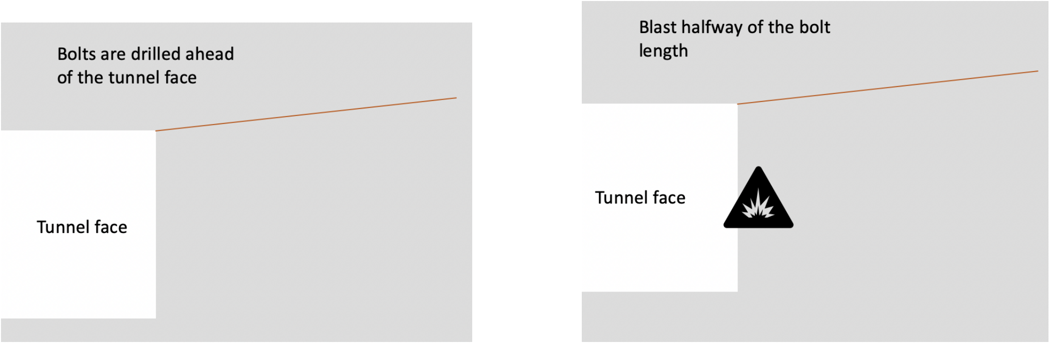
To determine support measures in tunnel constructions, close attention to the rock behaviour and the purpose of the construction are needed (Norwegian Geotechnical Institute, 2015). Each rock support alternative has specific properties with pros and cons in different scenarios. The behaviour of and interaction between these support measures and the rock mass always comes with some level of uncertainty (Zhao et al., 2021). Experience, preinvestigations and in situ measurements increase the likelihood of the chosen support measure being adequate. According to Gerolymatou (2020) supportive measures are often divided into two categories, rock reinforcement and rock support. Rock reinforcement measures aim to enhance the rock mass own bearing capacity. Rock supports are measures that often works on the profile of the tunnel and brings additional bearing capacity. Following sections will further review common support measures used in tunneling projects.

3.2.1 Rock reinforcement

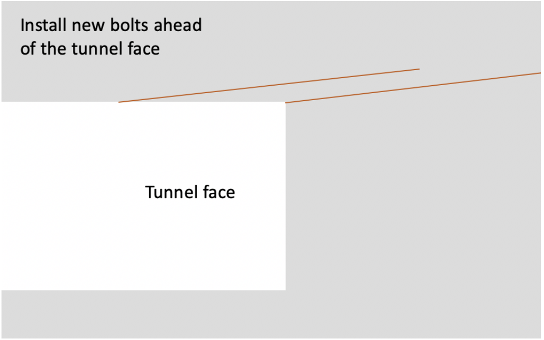
Rock bolting is commonly used in tunneling excavations. It is conducted by drilling steel bolts into the rock mass and connecting them to plates at the tunnel profile. The spacing between the bolts can be both individually assessed or predetermined with a set spacing pattern. Rock bolts are a multipurpose support measure that can both secure individual rock blocks but also work as a anchor for the shotcrete anchor. In those cases where rock bolts are used in combination with shotcrete some attention needs to be taken of punching phenomena. This is a failure mechanism where the plate at the end of the rock bolt fails (Ansell, 2009).

The surface of a tunnel profile are more or less irregular. This irregularity are shown in several studies to have an impact on the efficiency of rock bolts. The results indicates a higher bearing capacity if the rock bolts are placed on peaks, of the irregular profile, and not on depressions (Ansell, 2009; Nilsson, 2003). Therefore, some flexibility in the rock bolt placement might be desired.

In poor rock conditions or where there is shallow rock coverage it might be necessary with pre-bolting/spiling. Spiling is the concept of bolting ahead of the tunnel face. This reduces the risk of rocks and blocks falling down directly after blasting. Thus, the tunnel profile will not be compromised. It is conducted by drilling bolts along the tunnel profile, ahead of the tunnel face and with a slight inclination see figure 3.1. Thereafter, blasting is proceeded for half of the bolt length so that the bolt is still anchored to the tunnel face. When the rock mass has been removed a new bolt can be installed in the same way and the process restarts. Spiling is mainly a temporarily support measure but it could also be incorporated into the permanent support (Lindfors et al., 2019; Norwegian Geotechnical Institute, 2015).



(a) *Spiling bolt is installed ahead of tunnel face.* **(b)** *Blasting is conducted until half of the spiling bolt is reached.*



(c) *Next spiling bolt is installed and the procedure repeats.*

Figure 3.1: *The figures a-c shows a schematic visualization of a general stepwise procedure of spiling (authors own work).*

Injection as a support measure in tunnel projects is used to stabilise weakness zones before blasting, ahead of tunnel face (Barton & Quadros, 2019; Norwegian Geotechnical Institute, 2015). This, procedure is often utilized in weak rock with soil like behaviour and where problems with groundwater are expected. Injection can for example be conducted by pumping in grout via boreholes ahead of the tunnel face. This is often referred to as cement grouting or jet grouting. The cement fills out cracks and caverns and thereby stabilises the rock mass. Also, injection possesses the additional benefit of reducing water intrusion by ceiling of the cracks. Injection is used as a temporarily support measure that increases the stand-up time, which is the time the tunnel can stay unsupported without collapsing, before the permanent support is installed.

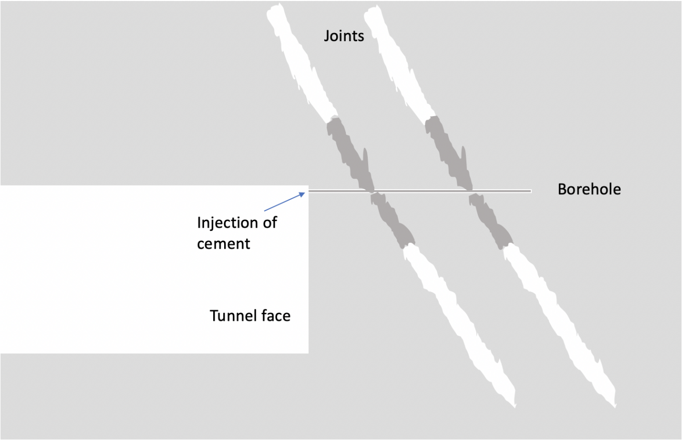


Figure 3.2: *Schematic representation of the injection process where cement grout are injected into cracks and caverns ahead of the tunnel phase (author's own work).*

Freezing is a support measure that, similarly to injection, temporarily increases the stability of the rock mass. Freezing is mostly used in soil but in very poor rock, almost soil like, freezing can be used. Tubes are injected via boreholes into the rock mass ahead of the rock face. Thereafter, cold fluids, e.g nitrogen, are circulated through the tubes and freezes the saturated groundwater in the soil or the water in rock cracks and caverns (Norwegian Geotechnical Institute, 2015).

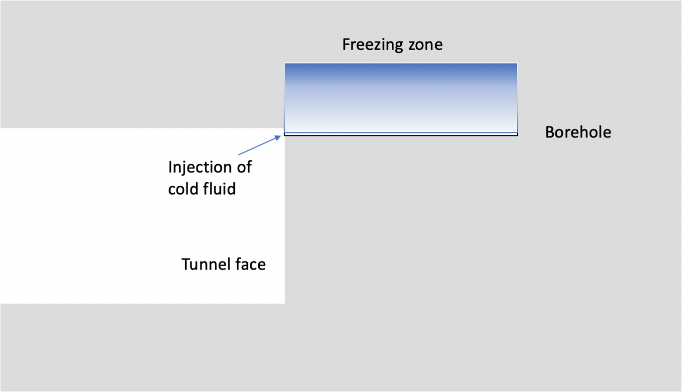


Figure 3.3: *Schematic representation of the freezing process where cold fluid are circulated in borehole, freezing the saturated water in the soil or very poor rock mass (author's own work).*

3.2.2 Surface support

The general beneficial properties of concrete steel structures are the bearing capacity in compression. The bearing capacity is commonly lower in bending where tensile forces are expected. Steel reinforcement is often added to improve the ability to withhold tensile forces. However, the capacity is still not as high as in compression. By creating an arch structure, more of the compressive properties can be utilized, resulting in higher bearing capacity (Nilsson, 2000). This is commonly referred to as dome action. In tunnels, concrete steel structures shaped as domes are suitable due to the common arch like shape of the profile. Structures that work at the tunnel profile as permanent support are often categorised as rock supports and some examples will be explained in this section.

There are many different types of steel structures that can be summarized under the term arches. Steel grids, rebars and girders are some examples (Gerolymatou, 2020). The scope of this thesis covers them all by using the general term of arches. Steel arches as a permanent support require some kind of corrosion protection. Shotcrete is commonly used to cover and protect these steel structures and serves as the same time as a support measure in itself. Thus, the steel arch and shotcrete cooperate as the support of the tunnel. However, the guidelines for designing these combined support structures are somewhat limited in Sweden.

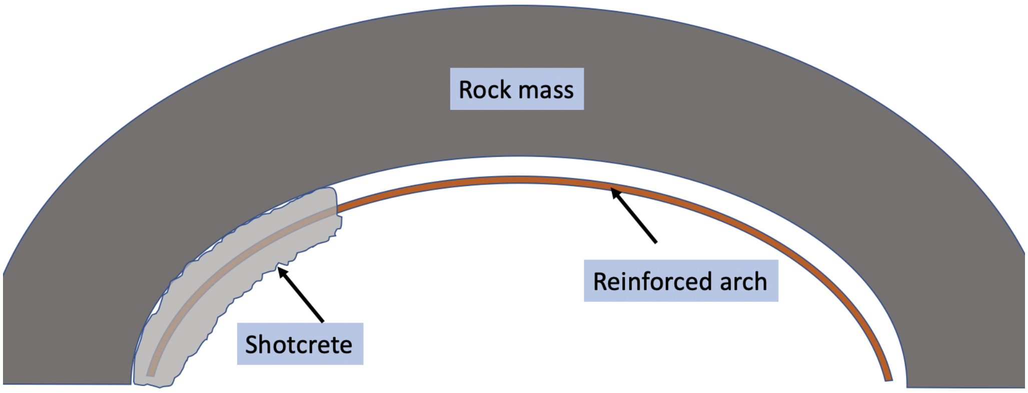


Figure 3.4: *Schematic visualisation of the concept of shotcrete arches where the reinforced steel in the form of an arch are covered with shotcrete, which is one type of surface support (author's own work).*

3.2.3 Wire mesh

Thin reinforcement steel arranged in a grid mesh is often referred to as wire mesh. The wired mesh is attached on the tunnel profile and is thereafter covered with shotcrete. The steel mesh improves the resilience to deformations and reduces the brittle behaviour of the shotcrete. However, as stated by Nilsson (2003) the surface of a tunnel profile is often irregular. This can complicate the installation of the mesh grid. Therefore, wire mesh is more and more replaced by steel fibres. Thus, removing the step of installation of mesh and ignoring the irregular shape of the profile (Nilsson, 2000).

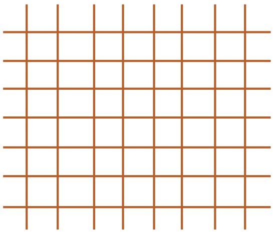
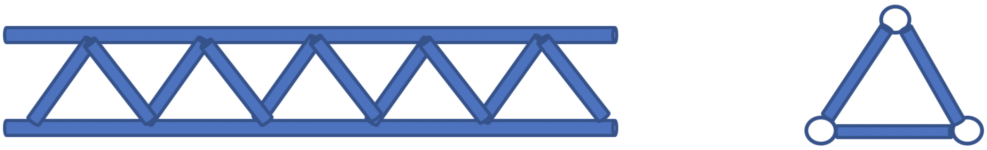


Figure 3.5: *Schematic figure of a wire mesh (author's own work).*

3.2.4 Lattice girder

Lattice girders are a alternative to the conventional rebar arch option. The difference between the two is that lattice girders are designed as a framework which reduces the required amount of steel while also increasing its surface. These properties are more resource effective and synergies well with shotcrete when there is more surface to attach to (Zhongsheng & Kaihang, 2019). Further, lattice girders are commonly built with hollow pipes that further reduces the material usage. There seems to be overall benefits with using lattice girders but further research is needed. At this point, lattice girders are not being used at large scale.



(a) *Framework*

(b) *Cross section*

Figure 3.6: *The graphs a and b show schematic figures of the cross section and framework of lattice girders (authors own work).*

3.2.5 Steel rib

Steel ribs are another support measure that is designed as a homogeneous steel beam formed as an arch. The cross section is like a I beam with the possibility to vary its dimensions. As for girders and rebars the rib follows the curvature of the tunnel profile. Steel ribs can provide a high bearing capacity but are also expensive and not as material efficient as for example lattice girders. However, ribs have in general a higher strength capacity then lattice girders (Gerolymatou, 2020).

Figure 3.7: *Shotcrete applied on steel reinforcement arches in access tunnel (Shotcreting Over Steel Ribs in Preparation for Waterproofing in Access Tunnel 4 (3-23-11), by MTA Construction and Development, 2011, Flickr, (https://www.flickr.com/photos/59595815@N03/5557948927). CC.)*

3.2.6 Steel rebar

Steel rebar shotcrete arches are commonly used in tunnelling projects in Sweden. These are the focus points of this thesis and are therefore in depth covered in section 3.4.

3.3 Shotcrete

Concrete in general, consists of cement, aggregate and some combinations of chemical additives. The concrete recipe can be modified to achieve different properties that suit the intended purpose. The difference in shotcrete and concrete is mainly its application. Instead of using casts the concrete is sprayed directly on the reinforcement and potential rock profiles. Shotcrete is therefore heavily reliant on its additive and fast hardening properties. Different accelerators are commonly used to start the hardening process directly after application (Norwegian Tunneling Society, 2010).

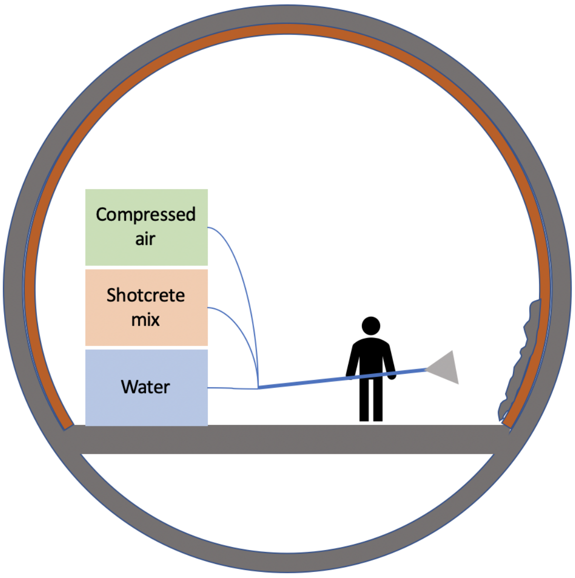


Figure 3.8: *Schematic representation of the application process of shotcrete on steel reinforcement arches in tunnels (author's own work).*

3.3.1 Synonyms

Concrete with steel reinforcements is a very common material combination to use in a wide range of construction projects. Concrete has the properties of withstanding compression while the steel reinforcement can withstand load in tension. These properties make the material combination very reliable and useful in various projects with high loads and stresses. This wide use is likely one factor that causes the numerous synonyms used in literature. To simplify the understanding of what words are used to describe shotcrete a list of synonyms is created below. This study will hereafter use shotcrete or reinforced shotcrete arch as terms that covers all synonyms listed.

Table 3.1: *List of English synonyms to shotcrete, arch and shotcrete arch that have been encountered in literature, during this project.*

English		
Shotcrete	**Arch**	**Shotcrete arch**
Sprayed concrete	steel ribs	-
-	steel sets	-
-	lattice girders	-
-	steel arch	-
-	reinforced arch	-
-	grid arch	-
-	steel mesh	-
-	rips	-

Table 3.2: *List of Swedish synonyms to sprutbetong, båge and sprutbetongbåge that have been encountered in literature, during this project.*

Swedish		
Sprutbetong	**Båge**	**Sprutbetongbåge**
-	stålbågar	betongbåge
-	förstärkningsbågar	sprutbetongbåge
-	valv	sprutbetongvalv

3.3.2 Additives to the shotcrete mixture

Shotcrete consists of several components that determine its properties. These can be summarized as accelerators, plasticisers, retarder, stabiliser, pumpability improver and internal curing and will be further covered in section 3.3.2.1-3.3.2.4. In general, the main purpose of shotcrete is to get fast adhesion to the rock and as strong initial strength as possible. For permanent support and long lasting constructions, the long term strength and durability are equally important. From an economical and environmental perspective it is of course also important to achieve this with as small amount of shotcrete as possible. According to Sakai et al. (2006) a shotcrete mixture with higher strength can in general be applied in a thinner layer, and thereby lower the cost.

3.3.2.1 Fibres

Shotcrete is as any other concrete mixture brittle when exposed to tensile forces (Shah et al., 2021). Therefore, steel fibres can be added to shotcrete mixture to get a more ductile response and thereby increase the bearing capacity and flexibility of the shotcrete. Steel fibres are a alternative to ordinarily types of steel reinforcement. These can sometimes be hard to arrange properly due to the often irregular shape of the tunnel profile. Thus, steel fibres can be a good alternative (Nilsson, 2003). However, the steel fibres in itself could corrode and sometimes act as a path for corrosion . Therefore, shotcrete with steel fibres might not be suitable when covering and protecting steel reinforcement, for example in reinforced shotcrete arches. The course of action in those cases could be using ordinary shotcrete around the reinforcement and shotcrete with steel fibre everywhere else. This is exemplified in Jonsson (2020), Jonsson and Andersson (2020), and Perman and Edelbro (2019).

3.3.2.2 Accelerators

The purpose of accelerators is to speed up the hardening process. This helps with the initial stability and adhesion to the rock surface. Historically, alkali silicates and alkali aluminates have been used. However, since these are not considered environmentally friendly and can constitute a hazard for the user, alkali free accelerators are more commonly used today (Norwegian Geotechnical Institute, 2015).

3.3.2.3 Plasticiser and super plasticiser

Since the availability of cement is getting scarcer a demand for supplements is increasing. Plasticisers and superplasticisers can be used as an alternative or supplement to cement in concrete mixture (Anaszewicz, 2021). These admixtures benefits the floating properties of the shotcrete while also reducing the required water content. Further, it increases the compressive strength but in combination with alkali free accelerators the initial strength might be lowered (Norwegian Geotechnical Institute, 2015).

3.3.2.4 Retarder or stabiliser

Retarder additives are used to delay or prolong the hardening process. This is essential in the use of shotcrete since the compound is pumped through tubes and should remain in liquid form until application. Also, by delaying the hardening process it is possible to more reliably provide the mix to the applying technician without the risk of running out or volumes going to waste. The use of retarder often increases the need for accelerators to counteract the slow hardening (Norwegian Geotechnical Institute, 2015).

3.3.3 Mechanical properties of shotcrete

Shotcrete can be used with or without steel reinforcements. As for any concrete structures the lack of reinforcement gives a brittle material that are sensitive for tensile stresses and bending (Shah et al., 2021). Therefore, constructions where deformations are expected some kind of steel reinforcements are often required. However, shotcrete can be fully sufficient on its own. As stated by Nilsson (2003) there are three main bearing mechanism which are covered below.

Adhesion between the rock mass and the shotcrete is one main bearing mechanics of shotcrete. The adhesion between the rock and the shotcrete distributes the load onto the supports. To achieve good adhesion the surface need to be as clean as possible of organic content and water. Therefore it is important to address water intrusion issues beforehand, to avoid the shotcrete not sticking (Nilsson, 2003; Norwegian Geotechnical Institute, 2015).

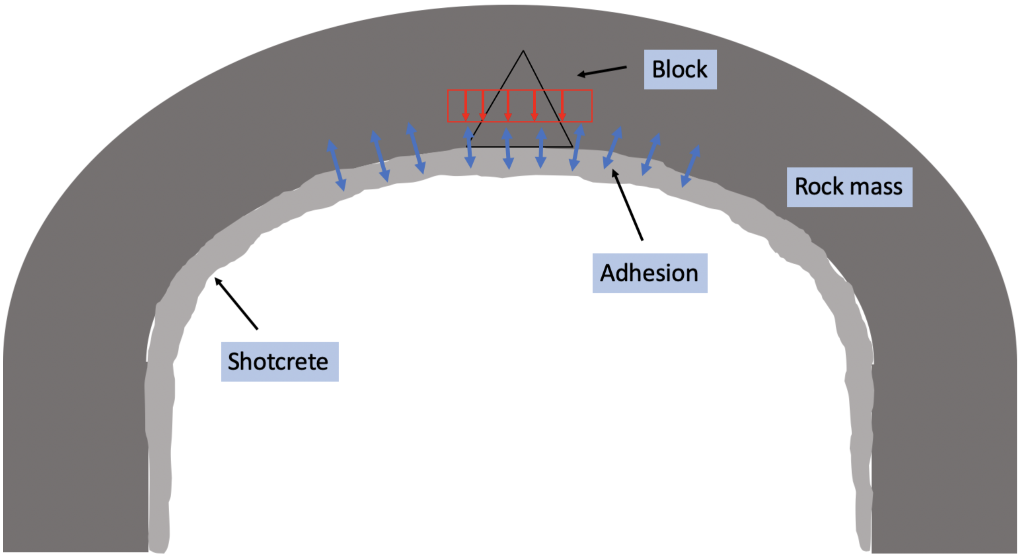


Figure 3.9: *Schematic visualisation of the concept of adhesion where the shotcrete attaches to the rock mass and keeps for example rock blocks in place (author's own work).*

Deformations in the rock mass will cause strains on the applied shotcrete due to bending. When steel fibres are added to the shotcrete mix there will also be a bearing mechanism in bending. The steel fibres hold the concrete together when it cracks.

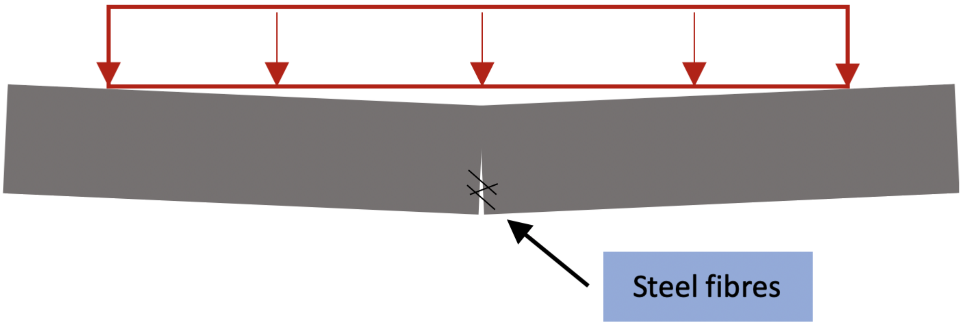


Figure 3.10: *Schematic visualisation of the concept of bending where the steel fibres in the shotcrete mix counteracts cracking (author's own work).*

If the shotcrete are anchored to the rock with bolts some compressive arch action can be expected. This is when the cross section of the shotcrete is pressed against each other as a result of bending. This results in a withholding moment

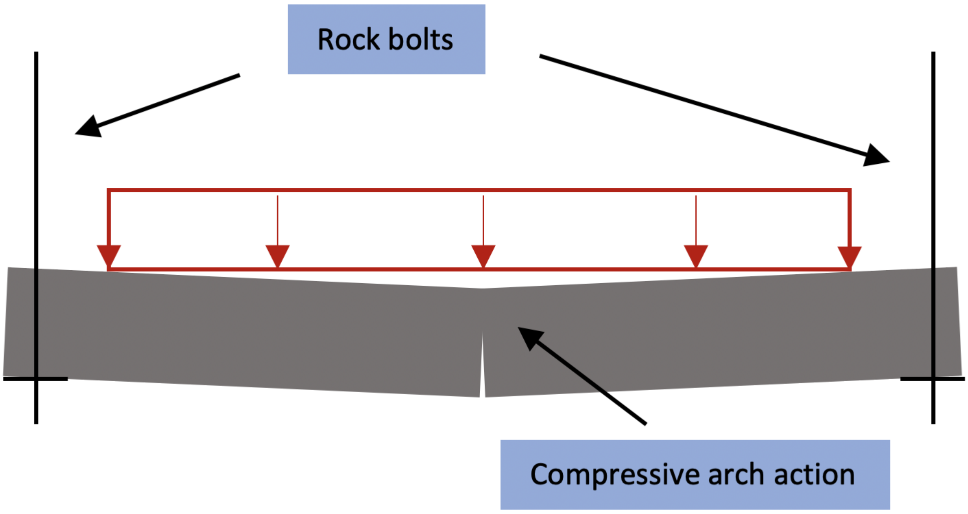
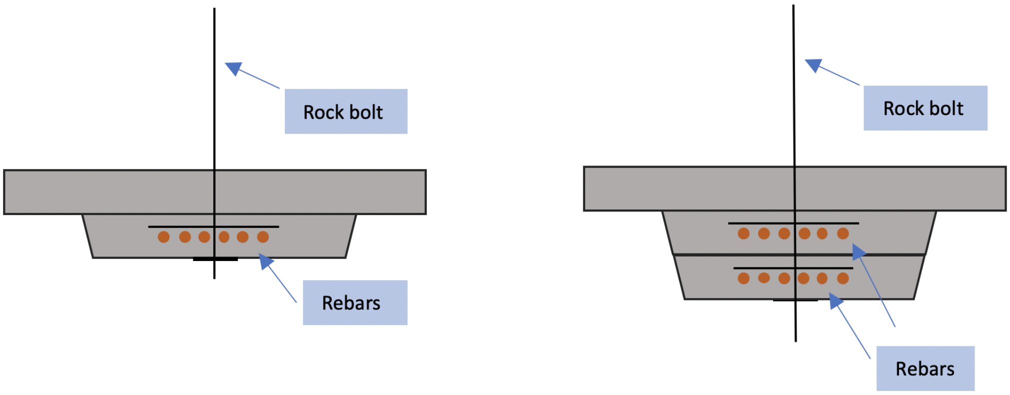


Figure 3.11: *Schematic visualisation of the concept of compressive arch action where the shotcrete gets fixed between the rock bolts in the form of an arch are covered with shotcrete (author's own work).*

3.4 Reinforced steel rebar shotcrete arch

Steel rebars are commonly used in Sweden. It is used where regular support, fibre shotcrete and rock bolts, is not sufficient. Steel rebars are installed stepwise. First the surface of the profile needs to be smoothed. Therefore, a layer of shotcrete is firstly applied. Thereafter, is a layer of steel rebars installed. The exact design of these rebars is flexible and can be adjusted to the specific situation. Further, another shotcrete layer are applied to cover and protect the steel. Additional layers of rebars can be installed if needed. A second layer of rebars increases the bearing capacity and the shotcrete arch ability to withstand moment forces. Lastly, the rebars are often anchored to the rock mass with rock bolts, see figure 3.12 and 3.13 (Hjálmarsson, 2011; Pedersen et al., 2010).



(a) *Single layer of rebars* **(b)** *Double layer of rebars*

Figure 3.12: *The graphs a and b shows a schematic cross section of reinforced shotcrete arches with single or double layer of rebars (author's own work).*

Figure 3.13: *Photo of reinforced rebar arches before being covered with shotcrete (photo received form expert at the E4 Stockholm bypass project).*

3.4.1 Purpose

The purpose of using reinforced shotcrete arches in tunneling projects is to ensure the stability of the tunnel profile. Such support measure are often economically justified in difficult local conditions. Such situations where reinforced shotcrete arches may be an option are for example:

- Poor rock conditions, $Q < 0.1$ in general (Jonsson & Andersson, 2020)
- Thin rock coverage, in general rock coverage less then half the tunnel width (Perman & Edelbro, 2019)
- Local conditions with fault zones or presence of joints (Radoncic, 2016).
- Large tunnel widths, in general >21m (Eriksson, 2013)

3.4.1.1 Designing phase

In Sweden, engineers often use the guidelines written by Lindfors et al. (2019) to design and plan the construction of shotcrete arches. These guidelines cover lattice girders and steel arches which are translated to steel rebar shotcrete arches in this thesis. The guidelines for these arches are somewhat limited. As it stands, there are only simple explanations of the load behaviour on shotcrete arches where spiling is used. Hence there is no information of how to design shotcrete arches without spiling. However, it could probably be assumed that the load from spiling in this case could be replaced by any other load, for example loads from the rock mass.

The decision making process of when and why shotcrete arches should be implemented are described by simple flow charts (Lindfors et al., 2019). Small rock coverage, poor rock quality or wide weakness zones are stated as situations where shotcrete arches could be implemented. However one could easily think of more cases where arches could be useful, for example in tunnel interchanges and situations with wide tunnel span.

According to Lindfors et al. (2019) there are four different aspects that generally needs to be considered. These are:

- Shotcrete arches should be designed for the entire cross section and for local load cases.
- The shotcrete arch can be designed as free bearing as in no interaction with the rock mass.
- Alternatively the shotcrete arch can be designed as a structure where the shotcrete and the rock are interacting.
- The design can be conducted analytically or numerically.

When designing a shotcrete arch, it seems to be important whether the arch are anchored to the rock mass or not. If it is not anchored with rock bolts it could be viewed as a a stand alone steel and concrete structure. This could likely simplify the use and implementation of different Eurocodes, since these are more suitable and developed for different steel and concrete structures. However, if it is anchored to the rock mass the structure will interact with the rock mass, making it difficult to solely use Eurocode. Thus, expertise and experience of both structural and rock engineers would be needed to design the arch.

3.4.2 Requirements and recommendations

When reviewing requirement and recommendation documents available for tunneling construction it is noticeable that the information is very limited. It is further clearly stated by Athanasopoulou et al. (2019) that the available European standards, for example EN 1990 and EN 1999, are not suitable nor is it meant to be suitable in tunneling constructions. Athanasopoulou et al. (2019) further concludes that additional standards or extensions of the already available ones are needed that explicitly includes the constructions used in tunneling projects. Further, it seems like this process has started and that new documents will be presented in the future. However, as of right now engineers needs to rely on national requirements and recommendations or somehow apply the available, but not suitable, international standards when designing underground constructions.

In Sweden, there seems to be three main requirement documents that are used when designing support constructions in tunnels. These are "Projektering av bergonstruktioner" by Lindfors et al. (2019), different versions of Eurocode and TRVINFRA-00233. The difference between these are in general that TRVINFRA-00233 and "Projektering av bergkonstruktioner" takes the interaction with rock mass into account and Eurocode does not to the same extent. To be able to use Eurocode it is often required to simplify the problem and consider the shotcrete arch as a beam, which is further shown in chapter 4 section 4.2. However, even if the shotcrete arches are considered interacting with the rock mass Eurocode can be somewhat implemented in the design methodology, for example by providing certain partial factors. When studying these documents it becomes clear that regarding reinforced shotcrete arches the information is scarce. This is likely because shotcrete arches are a relatively new way of supporting tunnels. Only two reported cases have been found, the West link and E4 Stockholm bypass, where such arches have been designed and used. Overall, by combining these three supportive documents the document seems to be sufficient to construct reinforced shotcrete arches. However, it is likely that further development of these documents would benefit the design process of reinforced shotcrete arches.

Additionally, there are documents available that aid the process of applying Eurocode on underground constructions. For example, Implementeringskommisionen för Europastandarder inom Geoteknik (2010) provides an advisory document that aids the application of SS-EN 1997-1. The idea is that this application document can be used together with other documents such as SS-EN 1990 and SS-EN 1991 and also together with other application documents. Altogether, there are several documents, where no one is explicitly made for underground constructions, that the rock engineer needs to take into consideration when designing for example shotcrete arches.

4

Design of reinforced shotcrete arches

When approached with the problem of designing a reinforced shotcrete arch to support the rock mass profile in a tunnel, mechanical and structural engineers seems to opt into different methodology of doing this. This chapter exemplifies some of these methodology's used in the industry today.

4.1 Rock mechanical design principle

Rock mechanical engineers specialises in understanding rock behaviour with respect to rock characteristics, stresses, deformations etc. Therefore, it can be expected that the design process of various surface support measures are closely linked to the rock mass behaviour. Section 4.1 in this thesis illustrates the design process of reinforced shotcrete arches by showing examples from the procedures of the West link and E4 bypass. The general design procedure, for both of these cases, is shown in flow charts by Jonsson and Andersson (2020) and Eriksson (2013), however since it is in Swedish it is placed in Appendix 1 and 2.

The design process of the adequate support measure relies on empirical, analytical and numerical analysis where the combined result from these are used to determine the proper support measure.

It is important to understand that there is a difference between general support measures and custom support measures. The general support is predetermined and valid under certain circumstances and can be used repeatedly during the project. Custom support is specifically designed for local variances of for example very thin rock coverage. In the West link project for example, there are both a general design of shotcrete arches that can be used throughout the project, and custom design. Custom design is for example used in the service tunnel 206. In the West link project, general support where developed for the rock classes 1 to 4 and custom support where required otherwise (Jonsson, 2020).

4.1.1 Empirical analysis

The empirical analysis is often conducted by using the rock mass classification to determine a suitable support measure. The Q value was determined using the methodology described in section 3.1.1 of this thesis. The resulting Q values could be used to classify the rock, see table 4.1. Furthermore, rock class five was determined to be when $0.01 < Q < 0.1$ and when rock coverage is $< 5m$. This was mainly the case for example in some parts of service tunnel 206 (Bergman & Andersson, 2019; Perman & Edelbro, 2019). It is also further stated that if the conditions where $Q < 0.01$ and rock coverage are $< 2m$ the design developed for rock class five would need further adjustments.

Table 4.1: *Table showing the rock mass classification with respect to the determined Q-value at the West link project (Jonsson, 2020).*

Rock mass classification	Q values
1	$Q > 10$
2	$4 < Q < 10$
3	$1 < Q < 4$
4	$0.1 < Q < 1$

The design however, is not solely based on the rock mass classification. The span of the tunnel is, as one could imagine, also a limitation for the design. These spans are of course very different in different projects. In the West link project 3 spans where defined. These where 5 to 10 m, 10 to 17m and 17 to 21m and where named as span class A, B and C respectively (Jonsson, 2020; Jonsson & Andersson, 2020).

To determine the adequate support measures, with respect to Q values and tunnel spans, the diagram shown in figure 4.1 was used.

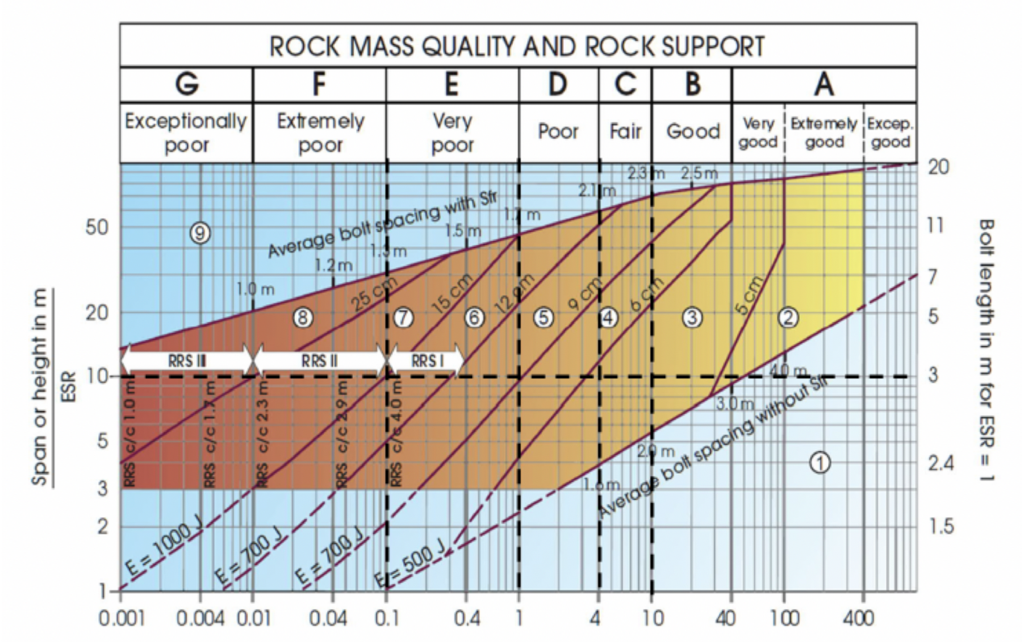


Figure 4.1: *Empirical diagram developed by Norwegian Geotechnical Institute (2015) to be able to convert the acquired Q-value into a corresponding support measure.*

The results from using this methodology are shown in table 4.2 to 4.4, for the general support. RRS1 for the reinforced shotcrete arch design was defined as, 6 rebars in one layer with a diameter of 16 to 20 mm. This should be covered with 300 mm of shotcrete and the center to center spacing between each arch where determined to 4 m. RRS2 was determined to 6+4 rebars in two layers with a diameter of 16 to 20 mm. It should be covered with 550 mm of shotcrete

Span class A $(5 < B \leq 10)$					
Rock class	Q-value	Bolt distance, S [m]	Bolt length, L_b [m]	Fibre reinforced shotcrete [mm]	Shotcrete arch
1	10	2.3	3	55	-
2	4	2.1	3	60	-
3	1	1.7	3	90	-
4	0.1	1.3	3	150	RRS1 c/c 4.0m

Table 4.2: *Results for the general support at the West link project for span class A (Jonsson & Andersson, 2020).*

Span class B $(10 < B \leq 17)$					
Rock class	Q-value	Bolt distance, S [m]	Bolt length, L_b [m]	Fibre reinforced shotcrete [mm]	Shotcrete arch
1	10	2.3	4.3	57	-
2	4	2.1	4.3	70	-
3	1	1.7	4.3	105	-
4	0.1	1.3	4.3	200	RRS2 c/c 4.0m

Table 4.3: *Results for the general support at the West link project for span class B (Jonsson & Andersson, 2020).*

Span class C $(17 < B \leq 21)$					
Rock class	Q-value	Bolt distance, S [m]	Bolt length, L_b [m]	Fibre reinforced shotcrete [mm]	Shotcrete arch
1	10	2.3	5.7	60	-
2	4	2.1	5.7	90	-
3	1	1.7	5.7	120	-
4	0.1	1.3	5.7	250	RRS2 c/c 4.0m

Table 4.4: *Results for the general support at the West link project for span class C (Jonsson & Andersson, 2020).*

For rock class five however, which is the case at some sections in service tunnel 206 with a Q value of 0.02 at worst. The empirical design shown in table 4.5 was determined with the Q method. The reinforced shotcrete arches where determined to RRS2 witch 6+2 rebars in two layers with a diameter of 16 to 20 mm. The shotcrete coverage are 450 mm and the center to center spacing where 2.5 m.

Tunnel span of 6.7 m						
Q-value	Tunnel width [m]	ESR	Bolt length L_b [m]	Bolt distance S [m]	Shotcrete thickness [mm]	Shotcrete arch
0.02	8.7	1	2.9	1.1	200	RRS2 c/c 2.5m

Table 4.5: *Results for the custom support at the West link project in the service tunnel 206 (Perman & Edelbro, 2019)*

4.1.2 Analytical analysis

The analytical analysis can be conducted for both bolts and shotcrete.

For the general design at the West link project the analytical analysis is following the developed methodology of Bjurström and Heimersson (1979). Similar methodology where also used at the E4 Stockholm bypass project (Radoncic, 2016) This is a stepwise procedure and are conducted as follows:

1. Estimate the tunnel span B and crack width e.
2. Calculate bolt length L_b by using equation 4.1 to 4.3

$$L_b \geq \frac{B}{3} \qquad \text{if} \quad B < 6m \tag{4.1}$$

$$L_b \geq \frac{B}{4} \qquad \text{if} \quad B \geq 6m \tag{4.2}$$

$$L_b > 3 * e \tag{4.3}$$

3. Calculate bolt distance S by using equation 4.4

$$S \leq 3 * e \tag{4.4}$$

4. Control the following relationship between bolt length and crack width.

$$S < 0.5 \ \ \text{to} \ \ 0.7 * L_b \tag{4.5}$$

5. Use the smallest value for S that is aquired from equation 4.4 and 4.5 as bolt length.

To avoid rock blocks falling down between the bolts shotcrete can be used as additional surface support. As explained in Jonsson and Andersson (2020) analytical analysis was also conducted for shotcrete at the West link project. The analysis is conducted with respect to the requirements in Lindfors et al. (2019). The shotcrete analysis is conducted for four different scenarios. These are:

1. Good adhesion and failure in adhesion
2. Bad adhesion and failure in bending
3. Punching of rock between bolts
4. Punching of bolt disk through shotcrete

Good adhesion was assumed where Q>4 and where set to 0.5 MPa. Bad adhesion was assumed when Q<4 and in that case adhesion where set to 0 MPa.

For scenario 1 Lindfors et al. (2019) describes three possible shapes of potential rock blocks falling out. These are cone, pyramid and wedge and at the West link it is assumed to be a case with a pyramid shaped rock block (Jonsson & Andersson, 2020). However, exactly why this is assumed is not stated. Furthermore, to determine the dimensioning load Wd for the pyramid, two equations, 4.6 and 4.7 from Fredriksson (1995) where used. The equations are slightly modified to be better adjusted to Eurocode (Lindfors et al., 2019). This methodology where also similarly used at the E4 Stockholm bypass project (Radoncic, 2016). These are:

$$Wd \leq \frac{\sigma_{adk} * \delta_m * O_m}{\gamma_C} * \pi * r \tag{4.6}$$

and

$$Wd = W_k * \gamma_d * \gamma_{G;dst} \tag{4.7}$$

Where:

σ_{adk} = Characteristic adhesion between shotcrete and rock mass
γ_m = Load withholding width between shotcrete and rock
O_m = Circumference of the load withholding surface between shotcrete and rock
γ_C = partial coefficient for the strength of the concrete
W_k = Characteristic weight of the rock block
γ_d = partial coefficient for the load
$\gamma_{G;dst}$ = partial coefficient for the load

It is stated by Holmgren (1979) and Stille et al. (1988) that there is a relationship between the thickness of the shotcrete layer T_c and the load bearing width γ_m. This relationship is shown in table 4.6

Thickness of the shotcrete layer, T_c [mm]	Load bearing width, γ_m [mm/m]
40	25
60	30
80	35

Table 4.6: *Relationship between the thickness of the shotcrete and the load bearing width (Holmgren, 1979; Stille et al., 1988).*

The acquired information of this analytical analysis can, according to Lindfors et al. (2019), be used to construct a diagram where the shotcrete thickness and bolt spacing with respect to the requirement of 0.5 adhesion is fulfilled. For example, at the West link project this methodology led to a bolt spacing of around 2 m and shotcrete thickness of 60 mm (Jonsson & Andersson, 2020). The general shotcrete thickness is relevant for the design of shotcrete arches since this thickness can be used as a minimum reference.

The remaining scenarios 2 to 4 are not covered further in this thesis. However, the general methodology is covered in Lindfors et al. (2019). Overall there are many different analytical analyse methodologies available and each of them are developed for certain circumstances.

4.1.3 Numerical analysis

Numerical analysis can be used both to determine adequate support measures but also to verify if the chosen support are sufficient. At the West link project, FLAC software has been used for the numerical analysis. It is described as a continuum and simulations are conducted for both in situ conditions, without support, and with the selected support measure. For the analysis without support the in situ plasticizing depth are modeled with respect to tunnel span and rock classification. The result showed that the worst case gravitational scenario for all span classes was in rock class four (Jonsson & Andersson, 2020). The result from these numerical analyses where also used in the analytical analysis of rock bolts.

The numerical analysis at the west link project for the general support was used to determine rock bolt length and bolt spacing in the roof for span class B and rock class four. For span class C the results from the numerical analysis where used to determine rock bolt length in rock class one to four and the bolt spacing for rock class four (Jonsson & Andersson, 2020).

Numerical analysis is also used to verify if the determined general support of shotcrete and rock bolts are sufficient. A worst case scenario was analysed and it showed that the determined length and spacing for the rock bolts and the thickness of the shotcrete layer where adequate, both for 30m rock coverage and a rock coverage of half the tunnel width. The results made it for example possible to reduce the bolt length form 6 m to 5 m for span class B, which made the solution more cost efficient (Jonsson & Andersson, 2020).

In poor rock conditions, as in some sections of service tunnel 206 numerical analysis has been used to determine if the selected shotcrete thickness is adequate. The analysis is conducted for three different sections of the tunnel with different rock coverage and Q_{bas}, see table 4.7. Three different strain types where evaluated which where gravitational strain, type-strain and maximum differential strains. The reinforcement in the model constitutes of 100 mm shotcrete. The results showed that for some strain types and rock coverage 100 mm of shotcrete where sufficient. However, in many cases the results were not satisfying and a safety factor >1 were not achieved (Perman & Edelbro, 2019).

Section	Tunnel width [m]	Rock coverage [m]	Q_{bas}
0/150	8.7	12, smooth ground surface	1 (-4)
0/260	8.7	20, simplified to smooth ground surface	0.1
0/240	8.7	30, smooth ground surface	0.1

Table 4.7: *Sections that have been numerically analysed in service tunnel 206 at the West link project (Perman & Edelbro, 2019).*

At the E4 Stockholm bypass project numerical analysis has been conducted in Phase2 software. Reinforced shotcrete arches are needed due to weakness zone 226 which crosses the main tunnel and some other parts of the development aswell (Guillemet, 2017; Radoncic, 2016) The chosen numerical models are based on local conditions. Two models were created for two different cross section. Model 1 was for the main tunnel with weakness zone in the roof. Model 2 was at the junction between the main tunnel and an evacuation tunnel where a longitudinal reinforced shotcrete arch can be examined. The model geometry was set to mimic reality as much as possible with fixed vertical displacement at bottom boundary and fixed horizontal displacement at side boundary. The rock mass properties were set as in table 4.8

Rock class	Q_{bas} [-]	c [MPa]	ϕ [°]	E [GPa]	ν [-]	Dilatancy [°]
3	$1 < Q_{bas} < 4$	1	45	10	0.25	0
4	$0.1 < Q_{bas} < 1$	0.5	30	3	0.25	0
fault	-	0.075	20	0.75	0.3	0

Table 4.8: *Characteristic rock mass properties (Guillemet, 2017)*

Thereafter, the joint sets where examined and parameters where determined as in table 4.9

Joint set	J_a	J_r	c [kPa]	ϕ [°]	k_n [GPa/m]	k_s [GPa/m]
1	4	1.5/2	150/210	21/22	6	0.6
2	4	1.5	150	21	6	0.6
3	4	2	210	22	6	0.6

Table 4.9: *Parameters of rock joints (Guillemet, 2017)*

Vertical stress, horizontal stress in plane and horizontal stress out of plane are determined by equation 4.8 to 4.10.

$$\sigma_y = 0.032 * z \tag{4.8}$$

$$\sigma_x = c_{cred} * 5.8 + 0.075 * z = 1.16 + 0.075z \tag{4.9}$$

$$\sigma_z = c_{cred} * 3.5 + 0.0275 * z = 0.7 + 0.0275z \tag{4.10}$$

The shotcrete lining was modeled as a 1D elastic beam element and the properties are presented in 4.10 and 4.11.

	Shotcrete grade	Thickness [mm]	Moment of inertia $[m^4/m]$	Poisson's ratio [-]	Weight density $[kN/m^3]$
Shotcrete	C32/40	200	$6.67 * 10^{-4}$	0.25	25

Table 4.10: *Shotcrete properties (Guillemet, 2017)*

	Age	Young's Modulus, E [GPa]	Compressive strength, σ_c [MPa]
Shotcrete	Early age shotcrete	5	8
Shotcrete	Mature shotcrete	16	32

Table 4.11: *Shotcrete strength and stiffness (Guillemet, 2017)*

The reinforced shotcrete arches where implemented in different ways in model 1 and 2. In model 1 the shotcrete arches had a center to center spacing of 1.5 m and a shotcrete thickness and width of 400 mm and 500 mm respectively. The design can be found in section 5.2.1 figure 5.7 of this thesis. The general shotcrete thickness is 200 mm. To be able to model reinforced shotcrete arches a transformation was needed where the arch can be considered a beam element. The input values for the transformation are shown in table 4.12. The number of elements are calculated as $1/s$ were s is the center to center spacing of arches. Therefore the number of elements is 0.667.

Parameter	Shotcrete	Reinforced shotcrete arch
Thickness	0.2	0.4
Width	1	0.5
Area	0.2	0.2
Moment of inertia	$6.67 * 10^{-4}$	$2.67 * 10^{-3}$
E-modulus	16000	16000

Table 4.12: *Input values for transformation (Guillemet, 2017)*

The input values are thereafter transformed with the methodology presented by Carranza-Torres (2004) as:

$$h_{eq} = 2 * \frac{\sqrt{3 * C_A * C_1}}{C_A} = 0.316m \tag{4.11}$$

$$E_{eq} = \frac{\sqrt{3}}{6} * \frac{C_A^2}{\sqrt{C_A * C_1}} = 13492MPa \tag{4.12}$$

Where:

$$C_A = n * (A_1 * E_1 + A_2 * E_2) \tag{4.13}$$
$$C_1 = n * (I_1 * E_1 + I_2 * E_2) \tag{4.14}$$

The results for the transformation for model 1 and 2 are presented in table 4.13 and 4.14.

	Shotcrete grade	Thickness [mm]	E-modulus [MPa]	Poisson's ratio [-]	Weight density $[kN/m^3]$
Reinforced shotcrete arch	C32/40	316	13492	0.25	25

Table 4.13: *Transformed reinforced shotcrete arch properties for model 1 (Guillemet, 2017)*

	Shotcrete grade	Thickness [mm]	E-modulus [MPa]	Poisson's ratio [-]	Weight density $[kN/m^3]$
Reinforced shotcrete arch	C32/40	400	16000	0.25	25

Table 4.14: *Transformed reinforced shotcrete arch properties for model 2 (Guillemet, 2017)*

The transformed properties are put into the two model which are then ran with four calculation steps each. For model 1 these are:

1. Initial equilibrium
2. Pre-relaxation ahead of the tunnel face by reducing the load on the perimeter to **72%**.
3. Continued relaxation from **72%** to **45%** and installation of surface support (200mm shotcrete) with properties of initial hardening.
4. Full unloading and installation of reinforced shotcrete arches and bolts, the shotcrete properties are set to 28 days of hardening.

For model 2 these steps where slightly different, such as:

1. Initial equilibrium
2. Pre-relaxation ahead of the tunnel face by reducing the load on the perimeter to **72%**.

3. Continued relaxation from **72%** to **25%** and installation of surface support (200mm shotcrete) with properties of initial hardening.

4. Full unloading and installation of reinforced shotcrete arches and bolts, the shotcrete properties are set to 28 days of hardening.

Lastly the model is validated and optimised however the full methodology of this are not included in this thesis.

4.2 Structural engineering design principle

In early stages of the West link project structural calculations were performed to verify the bearing capacity of the design developed by empirical, analytical and numerical analysis. Moment and shear force capacity were calculated according to the Eurocode SS-EN 1992-1-1 (Bagheri, 2015). At the time the geometry was as presented in figure 4.2 and 4.3, and the calculation methodology for this design are presented in section 4.2.1 and 4.2.2.

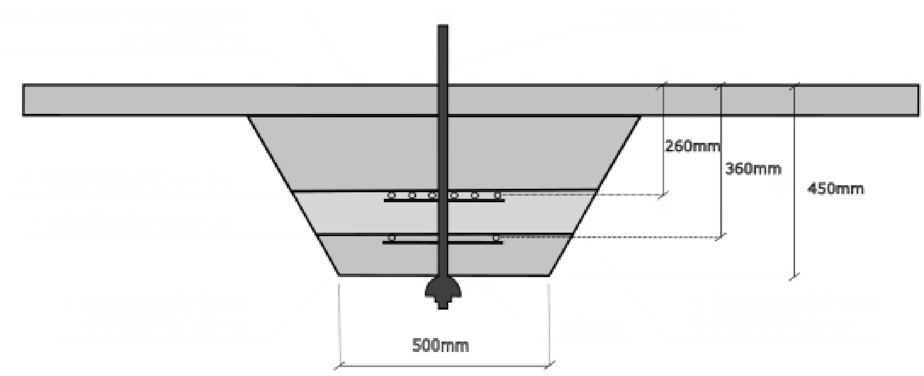


Figure 4.2: *Drawing of the cross section for reinforced shotcrete arches as general support for rock class four and span class B and C (Lesell, 2016) (modified by the author).*

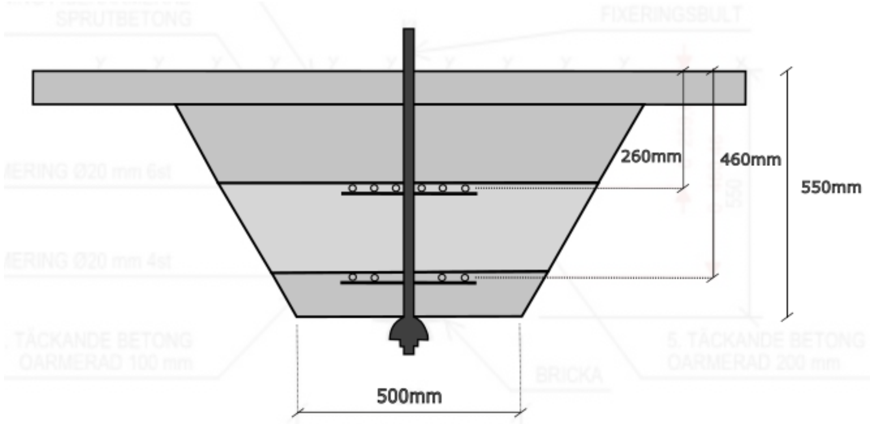


Figure 4.3: *Drawing of the cross section for reinforced shotcrete arches as general support for rock class four and span class B and C (Lesell, 2016) (modified by the author).*

4.2.1 Moment capacity

Some measurements where defined as: $b_{beam} = 500mm$, $h_{beam,A} = 450mm$ and $h_{beam,B,C} = 550mm$.

Effective height of the rebars where: $d_{1,A} = 360mm$, $d_{2,A} = 260mm$, $d_{1,B,C} = 460mm$ and $d_{1,A} = 260mm$.

Material parameters where determined as:

$$\begin{aligned}
f_{ck} &= 25 \text{ MPa} \\
f_{ctk} &= 2.2 \text{ MPa} \\
E_{cm} &= 35 \text{ GPa} \\
f_{yk} &= 500 \text{ MPa} \\
E_s &= 200 \text{ GPa} \\
\alpha_{cc} &= 1.0 \\
\gamma_C &= 1.5 \\
\alpha_{ct} &= 1.0 \\
\gamma_S &= 1.15
\end{aligned}$$

Design values where:

$$f_{cd} = \frac{\alpha_{cc} * f_{ck}}{\gamma_C} = 23.333MPa \tag{4.15}$$

$$f_{ctd} = \frac{\alpha_{ct} * f_{ctk}}{\gamma_C} = 1.467MPa \tag{4.16}$$

$$f_{yd} = \frac{f_{yk}}{\gamma_S} = 434.783MPa \tag{4.17}$$

Rebar quantities where determined as:

$\phi_A = 16mm$, $\phi_{B,C} = 20mm$

$$\begin{aligned}
A_{s,1,A} &= 2 * \frac{\pi * \phi_A^2}{4} = 402.124mm^2 \\
A_{s,2,A} &= 6 * \frac{\pi * \phi_A^2}{4} = 1.206 * 10^{-3}mm^2 \\
A_{s,1,B,C} &= 4 * \frac{\pi * \phi_{B,C}^2}{4} = 1.257 * 10^{-3}mm^2 \\
A_{s,2,B,C} &= 6 * \frac{\pi * \phi_{B,C}^2}{4} = 1.885 * 10^{-3}mm^2
\end{aligned}$$

Moment capacity calculation where conducted for a beam and **span class A** as:

$$F_C = F_{s,1} + F_{s,2} \tag{4.18}$$

$$0.8x * f_{cd} * b = A_{s,1} * f_{yd} + A_{s,2} * f_{yd} \tag{4.19}$$

$$x_A = \frac{A_{s,1} * f_{yd} + A_{s,2} * f_{yd}}{0.8 * f_{cd} * b_{beam}} \tag{4.20}$$

Control of rebar tension are performed as:

$\epsilon_{cu} = 3.5 * 10^{-3}$

$$\epsilon_{s,1,A} = \frac{d_{1,A} - x_A}{x_A} * \epsilon_{cu} = 0.013 \tag{4.21}$$

$$\epsilon_{s,2,A} = \frac{d_{2,A} - x_A}{x_A} * \epsilon_{cu} = 8.645 * 10^{-3} \tag{4.22}$$

$$\epsilon_{sy} = \frac{f_{yd}}{E_s} = 2.174 * 10^{-3} \tag{4.23}$$

$$\epsilon_{s,1,A} \geq \epsilon_{s,2,A} \geq \epsilon_{sy} \qquad \text{OK}$$

A mean value for the effective height are calculated:

$$d_{m,A} = \frac{A_{s,1,A} * d_{1,A} + A_{s,2,A} * d_{2,A}}{A_{s,1,A} + A_{s,2,A}} \tag{4.24}$$

And ductile requirement where checked:

$$\frac{x_A}{d_{m,A}} = 0.263 => \frac{x_A}{d_{m,A}} < 0.45 \qquad \text{OK}$$

Moment capacity where calculated as:

$$\begin{split} M_{Rd,A} = 0.8 * f_{cd} * b_{beam} * x_A * (d_{1,A} - 0.4 * x_A) - \\ f_{yd} * A_{s,2,A} * (d_{1,A} - d_{2,A}) = 178.353 kNm \end{split} \tag{4.25}$$

Similar methodology where conducted for **span class B and C** and resulted in a moment capacity as:

$$\begin{split} M_{Rd,B,C} = 0.8 * f_{cd} * b_{beam} * x_{B,C} * (d_{1,B,C} - 0.4 * x_{B,C}) - \\ f_{yd} * A_{s,2,B,C} * (d_{1,B,C} - d_{2,B,C}) = 384.45 kNm \end{split} \tag{4.26}$$

4.2.2 Shear forces

The shear force were calculated according to SS-EN 1992-1-1 chap 6.2.2 and the methodology is shown below:

$$V_{Rd,c} = \left(C_{Rd,c} * k * (100 * \rho_1 * f_{ck})^{\frac{1}{3}}\right) * b_{beam} * d \tag{4.27}$$

Where the input parameters were calculated as:

$$\begin{aligned} C_{Rd,c} &= \frac{0.18}{\gamma_C} = 0.12 \\ k_A &= 1 + \sqrt{\frac{200mm}{d_{1,A}}} = 1.745 \\ k_{B,C} &= 1 + \sqrt{\frac{200mm}{d_{1,B,C}}} = 1.659 \\ \rho_{1,A} &= \frac{A_{s,1,A} + A_{s,2,A}}{b_{beam} * d_{m,A}} = 0.011 \\ \rho_{1,B,C} &= \frac{A_{s,1,B,C} + A_{s,2,B,C}}{b_{beam} * d_{m,B,C}} = 0.018 \end{aligned}$$

When put into equation 4.27 the results where:

$$V_{Rd,c,A} = C_{Rd,c} * k_A * \left(100 * \rho_{1,A} * \frac{f_{ck}}{MPa}\right)^{\frac{1}{3}} * b_{beam} * d_{m,A} * MPa = 101.649kN \quad (4.28)$$

and

$$V_{Rd,c,B,C} = C_{Rd,c} * k_{B,C} * \left(100 * \rho_{1,B,C} * \frac{f_{ck}}{MPa}\right)^{\frac{1}{3}} * b_{beam} * d_{m,B,C} * MPa = 135.833kN \quad (4.29)$$

5

Case study review

The cases that have been reviewed in this study have at some occasion during the projects utilized reinforced steel rebar shotcrete arches as a support measure. This support construction has historically not been used frequently. It is in recent years and in ongoing projects that this solution has been implemented in Sweden. Unfortunately this means that the available documentation is somewhat scarce and hard to come by. However, it seems like these reinforced steel rebar shotcrete arches are implemented more and more thus it is likely that more documentation will be available in the future. This thesis aims to contribute to this.

5.1 West link project

The west link project initiated its construction in 2016 and is set to be finished in 2026. It is an eight kilometres railway tunnel that will provide Gothenburg inner city with for instance three new stations. This development aims to increase the railway capacity and reduce the commute times. The west link project is part of the West Swedish package which is a national investment in several infrastructure projects in Sweden (Swedish Transport Administration, 2021c). The total cost is expected to be 20 billion Swedish crowns and a total of approximately 1.7 million m^3 of rock are to be excavated (Lindblom, 2018).

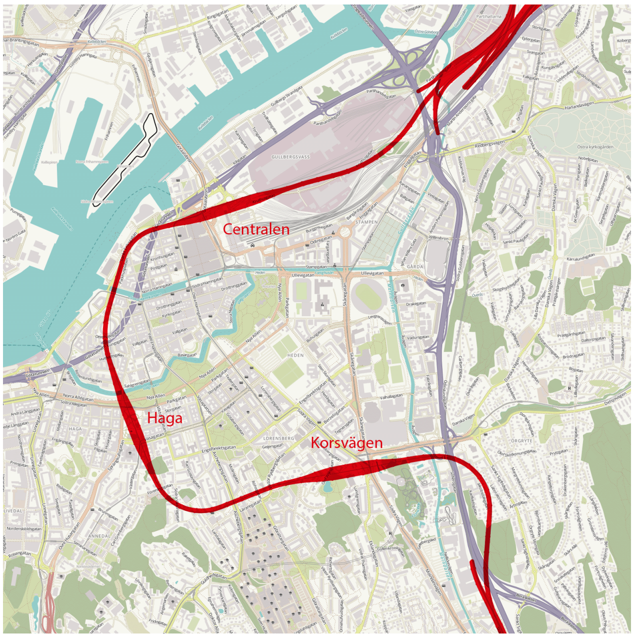


Figure 5.1: *Map of where the West link railway line is planned and where the new stations will be located. This figure is retrieved from Wikimedia common (2015)*

According to Swedish Transport Administration (2021a) the general excavation procedure consists of six steps. Step one is sealing of cracks and caverns to counteract water intrusion ahead of the tunnel face. This is done by drilling boreholes and thereafter injecting cement and water. Step two is the preparation for the blasting. 170 to 180 boreholes are drilled with varying depth depending on the rock mass quality. More sensitive rock mass requires less blasting depth and vice versa. Step three is the blasting step and is conducted in only a few seconds. However, the blasting is thoroughly thought through and is conducted with precise patterns and timings. The blasting procedure is quite complex and is only briefly touched upon here. Step four is the aftermath after blasting. Loose blocks and rocks that have not yet fallen down are scraped and knocked off the tunnel face. This is can be done both with machines and by hand. Extensive experience is required to conduct this step safely. Step five is somewhat connected to step four and is the loading and removal of the blasted rock mass. Rock masses are in general much heavier than soil masses and require therefore more truck loads per cubic meter mass. This is important to consider from an environmental point of view. Step six is the installation of adequate support measures. The west link project used in general shotcrete on the tunnel profile with the addition of rock bolts. However, in fault zones with poor rock mass quality additional support has also been implemented.

5.1.1 Reinforced shotcrete arches as general support

To determine if reinforced shotcrete arches are necessary some categorisation of the rock mass quality, the tunnel span and geological domain is needed. At the west link project, three different drawings of arches where made to be used as general support for different tunnel spans. The spans defined were 5 to 10 m, 10 to 17 m and 17 to 21 m and these were classified as span class A to C respectively. Further the use of arches also depends on the rock mass classification and this was done using Q values. The classes were between one to five and were defined as shown in chapter 4 table 4.1. Only in rock mass class four would reinforced shotcrete arches be needed (Jonsson, 2020). Further, under conditions where the Q value is even worse than in rock mass class 4 or if the rock coverage is less than half the tunnel span, individual assessment is needed. The structural geological domains were also considered where two different classes were determined. These were SGD3 and SGD4 where SGD4 were only relevant for span class A.

Empirical, analytical and numerical analyses have been conducted to determine adequate support measures at the west link project. The methodology and results from these analyses have been covered in chapter 4 of this thesis. The result are in conjunction with the experience of the engineers the basis for the final design. In general, the most conservative solution is selected. Bolt length and spacing are also rounded up (Jonsson & Andersson, 2020).

In summary, three different drawings of reinforced shotcrete arches where developed to be part of the general design in the West link project. These where determined in two steps. Firstly the minimum required design was created and secondly this design was adjusted to be suitable for production. More specifically, span class A was designed as RRS1 with one layer of 6 rebars with a diameter of 16-20 mm and covered with 300 mm of shotcrete, span class B and C was determined to RRS2 with two layers of 6+4 rebars with a diameter of 16-20 mm and were covered with 550 mm shotcrete. The cc spacing between each arch was determined to 4 m for all span classes (Jonsson & Andersson, 2020). The drawings of these are included in figure 5.2 and 5.3.

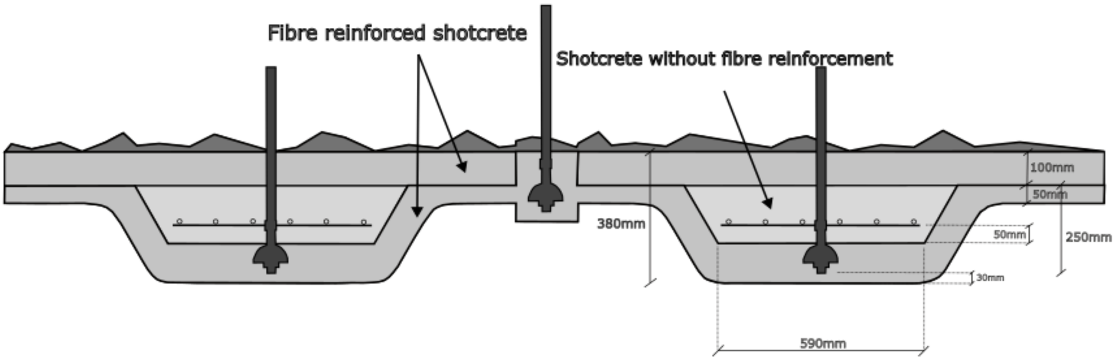


Figure 5.2: *Drawing of the cross section for reinforced shotcrete arches as general support for rock class four and span class A (Lesell, 2015)(modified by the author).*

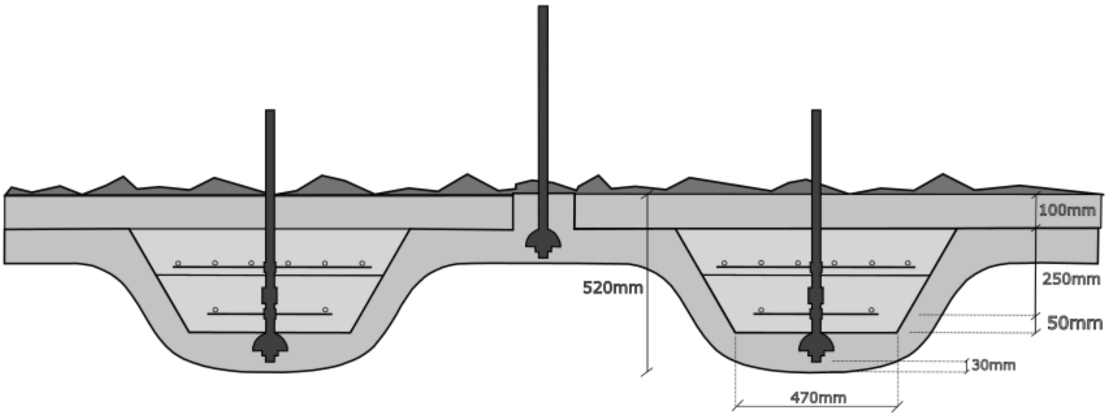


Figure 5.3: *Drawing of the cross section for reinforced shotcrete arches as general support for rock class four and span class B and C (Lesell, 2016) (modified by the author).*

5.1.2 Service tunnel 206

To verify the selected support measures that are chosen in service tunnel 206, empirical, analytical and numerical analyses have been conducted. The result from these analyses is used to determine suitable support measures both for ordinary conditions and for more challenging ones (Perman & Edelbro, 2019).

In situations with thin rock coverage and/or poor rock quality additional support measures are needed. At the West link project in the service tunnel 206, it was decided that a rock coverage of less than 5 m would require some type of more advanced support measure, regardless if the rock mass was classified as four or five with the Q system method (Bergman & Andersson, 2019).

The final design for the support measures used in service tunnel 206 where decided on the basis of the combined knowledge gained from the empirical, analytical and numerical analysis. For sections with poor rock quality $Q > 0.02$ a bolt length of 4 m and a spacing of 1 m were decided. Further, the shotcrete thickness where decided to 200 mm both on roof and walls (Perman & Edelbro, 2019)

The reinforced shotcrete arches constructed in service tunnel 206 where of the type RRS2 with two layers of rebars with 6 in the first layer and 2 in the second one, see figure 5.5. The rebars have a diameter of 16 mm and the center to center spacing between each arch is 2 m. When the rebars are in place they are covered with 450 mm thick layer of shotcrete where the closest layer to the rebars is without fibre reinforcement which minimizes the risk of corrosion in the steel rebars (Bergman & Andersson, 2019).

Figure 5.4: *Map showing the service tunnel ST206 at the Korsvägen part of the West link, where some shotcrete arches have been constructed (Bergman & Andersson, 2019).*

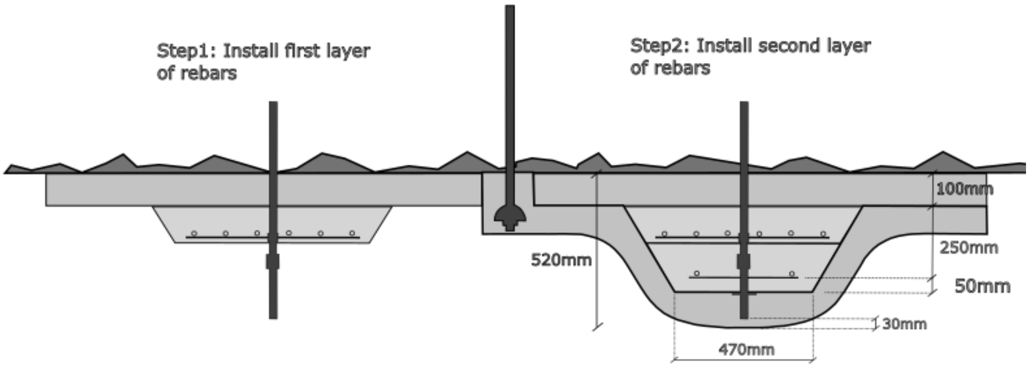


Figure 5.5: *Drawing of reinforced shotcrete arches as custom support for rock class four and five in service tunnel 206 (Larsson, 2019) (modified by the author).*

5.2 E4 Stockholm bypass

Stockholm bypass is a roadway project that connects euro road four between south and north Stockholm. It stretches a distance of 21 kilometers where 18 kilometers are in tunnel, see figure 4.2. With it's extensive length it is going to be one of the longest urban tunnels constructed in the world (Swedish Transport Administration, 2021b). The total cost for this project is around 34 billion Swedish crowns and 6.5 million m^3 of rock are to be excavated (Lindblom, 2018). The general excavation procedure is similar as in the West link project with rock bolting and shotcrete on the profile as primarily support measures. According to van Eldert et al. (2021)

the Q-system has been used to classify the rock mass. The corresponding support measures are linked to the classification. For rock mass class one to four rock bolt and shotcrete should be solely sufficient. However, for very poor rock quality, where the Q-value is less than 0.1, individual assessment is required.

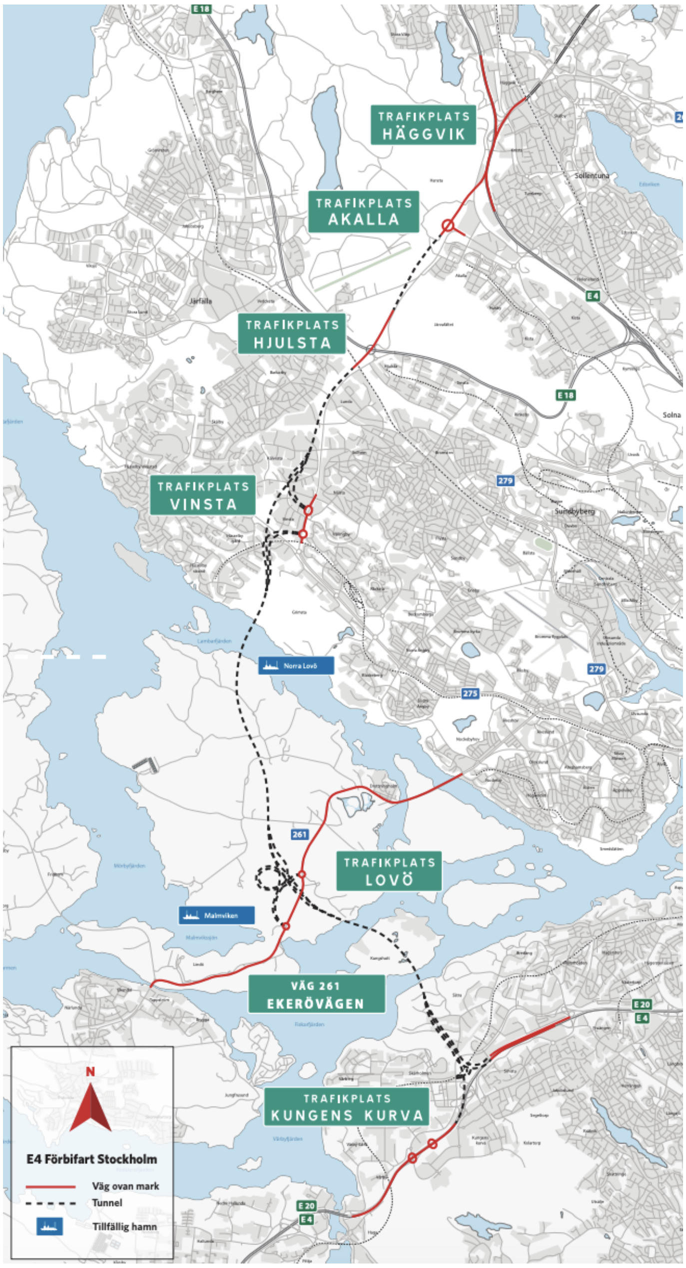


Figure 5.6: *Map of where the E4 Stockholm bypass roadway tunnel is planned and where the new interchanges will be located. This figure is retrieved from Swedish Transport Administration (2021b)*

5.2.1 Advanced support

Similar as in the West link project, custom designs of reinforced shotcrete arches have been conducted in sections with rock class five and span class B and C, also at E4 Stockholm bypass. Rock class five is defined as $0.01 < Q < 0.1$ and span class B and C are 12 to 17m and 17 to 21m respectively (Mettävainio, 2022). Numerical and analytical analysis was used, as described in section 4.1.2 and 4.1.3, to determine the design of bolts, shotcrete and reinforced shotcrete arches. The design, for rock class five, was determined to 200 mm shotcrete thickness and systematic rock bolting with bolt spacing 1.3 m and length of 5 m. The reinforced shotcrete arches were designed with 200 mm of shotcrete thickness and 500 mm width. The reinforcement consists of 8-10 rebars with a diameter of 16 mm. They are placed in two layers where there are less rebars in the first layer than in the second one, see figure 5.7. This design differs somewhat from the one conducted at the West link project. The spacing between each arch was decided to 1.5m

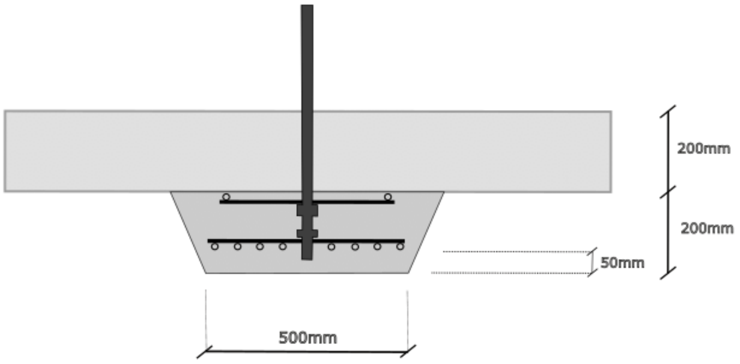


Figure 5.7: *Drawing of the design of reinforced shotcrete arches constructed at the E4 Stockholm bypass project in rock class five Steiner (2016) (modified by the author).*

6

Discussion

When designing reinforced shotcrete arches in tunneling projects there seems to be a fine line between strictly structural problems were the arches are viewed as stand alone concrete steel structures and when the arches are interacting with the rock mass. Whether it interacts determines how the problem could be approached. There is at this point no clear definition of where this line is drawn. This complicates the design process when there is no clear provision of who should design and what supportive documents should be used. As earlier mentioned in this thesis this line could be when or when not the arch is anchored to the rock mass. However, this is not broadly articulated. It is also not clear weather the general support bolting could also achieve this interaction. It seems like a standardised and clear distinction between when or when not the arch are interacting with the rock mass is needed. This would simplify the assignment of the correct competence and support documentation that are suitable to the problem. For example, whether a rock mechanical engineer or a structural engineer should do the design and whether TRVINFRA-00233, "Projektering av bergkonstruktioner" or Eurocode are the proper supportive documents.

It becomes clear when reviewing documents containing requirements and recommendations of designing reinforced shotcrete arches, such as Bergman and Andersson (2019), Jonsson (2020), Jonsson and Andersson (2020), Lindfors et al. (2019), Perman and Edelbro (2019), and Radoncic (2016) that there is little specific information on how to design these arches, both in Sweden and internationally. There are some clear empirical methodologies that closely link the rock mass classification to adequate reinforced shotcrete arch solution. However, in detail how this empirical connections are developed is not clearly described. It is likely that this methodology is based on extensive experience and well founded engineering assumptions which is probably adequate in an empirical environment. Further, empirical, analytical and numerical analyses are used in combination with each other and continuously validating the design. Altogether, the final design of reinforced shotcrete arches is likely well sufficient for its purpose. However, from an outside perspective it is hard to follow every step of the decision making process leading up to the final design, especially regarding reinforced shotcrete arches. It is therefore also not simple to evaluate if the chosen solution is adequate or if it is overdimensioned or even unnecessary.

It is evident, when reviewing building acts of the design process of reinforced shotcrete arches that there is very little explanation as to why the shotcrete arch is designed the way it is. There are well documented methodologies of the design of bolts and shotcrete thickness as part of the general support. But regarding shotcrete arches, both as part of the general support and in a custom situation, the final design is often presented without satisfying explanations. The empirical, analytical and numerical analyses are explained quite thoroughly, however exactly how the results from the analysis are connected to the final design suggestion is not easy to understand. The question then arises, why is it like this? It is certainly odd since it is not difficult to follow the connection between analysis and final design regarding bolt length and spacing and shotcrete thickness in the general support. According to the author of this thesis there is one likely explanation to why the documented methodology of reinforced shotcrete arches is insufficient. There is no clear methodology of designing reinforced shotcrete arches which forces the designer to use experience based decisions that are not documented. These decisions are thereafter validated in further analyses. It is therefore not easy to follow the decision making process regarding reinforced shotcrete arches.

Due to the complex nature of reinforced shotcrete arches, where the two fields of rock mechanics and structural engineering meet, problems with communication might arise. Both the literature and case study review conducted in this thesis has shown a broad usage of terminology that somewhat explains the same things. It could certainly be beneficial to unite under and agree upon understandable and consistent technical language, regarding underground construction in general and reinforced shotcrete arches specifically. Some compilation of encountered terms are included in this thesis. However, this merely scratches the surface of the wide terminology used and does not offer a solution to the problem. A more extensive mapping of this would likely simplify the communication on this topic, when a more uniform technical language are being used. Furthermore, it is likely that the present various amount of supportive documents, that are not sufficiently linked together, are further contributing to this issue.

When assembling a shotcrete arch there are several difficulties that need close attention. Due to the irregular shape of tunnel profile the steel rebars could also get a irregular shape. This is even more likely if rock bolts are used which could potentially push the rebars against the profile. This causes the arch to lose its intended shape which could result in reduced capacity. The convex arch shape is important to attain adequate arch action. Further, the spacing of the rebars are important. If there is narrow spacing between the rebars it could result in shadow zones behind it where the shotcrete can not reach. This, compromises the corrosion protection and could therefore reduce the lifespan of the arch. The assigned entrepreneurs of the project are responsible of avoiding the mentioned issues when constructing reinforced shotcrete arches. It is their job to construct the arches according to the drawings, requirements and tolerances. As mentioned rebar spacing, arch effect and bolting are sensitive moments that require experience and precision to conduct. It is therefore important that the drawings and instructions are easy to follow and understand.

6.1 Future prospect of the design process of reinforced shotcrete arches

In Sweden, elaborated methods to circumvent the problem with lacking requirements and recommendation have been developed. For example, conversion documents as in Implementeringskommisionen för Europastandarder inom Geoteknik (2010) are being used to better interpret and apply different Eurocodes in underground construction. Also, some of the equations and methodology described in Lindfors et al. (2019) are slightly modified to fit better with Eurocode. These methods seems to be working since underground constructions are continuously being developed. However, one could easily imagine the impracticalities of navigating several different Eurocodes and national application documents instead of having one or few dedicated documents for this purpose. It is evident, which is also stated by Athanasopoulou et al. (2019), that there is a clear demand for innovation and development regarding the supporting documents in underground constructions. Also, Athanasopoulou et al. (2019) further states that such supportive documentation is currently being developed. However, when this process will be finished and how the end result will look is unclear at this point.

6.2 Sustainability aspect

From an environmental perspective, an as efficient and optimised design as possible is desirable. This is because there would be less overdimensioning and wasting of resources. This is especially important regarding the general design decided in the project, since this design will likely be used frequently during the project. Even the slightest addition of for example 5 mm of shotcrete coverage could have large infliction on the total amount of shotcrete used. The study conducted in this thesis has shown that the design process of reinforced shotcrete arches is somewhat confusing to conduct. This is due to various amounts of support documentation that are limited and sometimes not intended for underground construction. It is somewhat likely that these shortcomings in requirements and recommendation are affecting the final design. Since there is a heavy safety responsibility on the designing engineer, to make a design that does not fail or collapse, it is understandable that the safety factors might be overly exaggerated. Especially when there is no clear documentation to refer to. For example, in the study conducted by Høien et al. (2019) it could be concluded that in some cases in Norway, were reinforced shotcrete arches where installed, it was not necessary to implement such support measures. If the guidelines where clear, the risk of overdimensioning and unnecessary use would probably decrease which would benefit the environment and make the design process of reinforced shotcrete arches more sustainable.

6.3 Ethical aspects

Currently, the design process of reinforced shotcrete arches seems to rely on experience based knowledge and/or supportive documents that are limited or not intended for such constructions. This makes it hard to follow the decision making process when reviewing building acts of these arches. Thus, in case of an incident or accident it will be difficult to backtrack what it was that went wrong. This is not ethically satisfying from an legal aspect. Also, it will not be possible to learn from such events so that it can be avoided in future developments of reinforced shotcrete arches. Hence, clarifications of the design methodology of such arches are needed to avoid ethical issues that might arise.

By creating a clear distinction when the rock is interacting with the rock mass there might be a reduction in work opportunities depending on where this distinction is made. For example if it is decided that all support constructions made in tunnels should be designed by rock mechanical engineers this likely inflicts on the amount of work available for structural engineers that might have done this before. It is overall likely that clear definitions on this topic will benefit the industry as a whole, however there might be significant economically consequences for the engineers and company's involved in designing reinforced shotcrete arches.

7

Conclusion

After reviewing the available literature and studying relevant cases regarding reinforced shotcrete arches, it is evident that there is room for improvements. It can be concluded that the available support documentation for designing shotcrete arches is not satisfying, both for national and international requirements and recommendations. It is therefore essential with further development on this area. As a suggestion, a collective document dedicated for underground constructions is desirable to simplify the design process of arches. Further, if it was possible to distinguish whether the reinforced shotcrete arches are interacting with the rock mass or not, it would likely simplify the design process of such. This is because then the correct competence could be assigned and suitable supportive documentation be applied. The general conclusions are listed below.

- There is not, as of right now, any clear definition that distinguishes whether a reinforced shotcrete arch interacts with the rock mass. This makes it difficult to differentiate when the reinforced shotcrete arch can or can not be considered a stand alone concrete steel structure, and thereby be designed as such.

- The requirements and recommendations of designing reinforced shotcrete arches are limited and need further development. The general support regarding shotcrete and rock bolts is clearly described in the methodology used at the West link and E4 Stockholm bypass. However, regarding reinforced shotcrete arches the connection between the analysis, empirical analytical and numerical, and the final design is not clearly described. One reasoning for this could be that the decision making process is mainly experience based, due to the lacking requirement and recommendation documentation.

7.1 Future work

During this project the author has been in contact with several experts on rock tunneling constructions. The overall impression is that this is a relevant topic which needs to be further studied and documented. However, it is overall hard to find relevant literature that addresses these issues. There seems to be consensus that the design process of reinforced shotcrete arches needs extensive development and many experts seem to be able to pinpoint these issues. Hence, by gathering the opinion and knowledge of experts on this topic, for example with some type of survey, a deeper understanding of the problem could be achieved. This would be another step of further developing the design process of reinforced shotcrete arches.

Since the background of the author of this thesis is within the rock mechanical and geotechnical field there are some limitations on fully comprehending the structural parts of designing shotcrete arches. Thus, further work on this topic could preferably be conducted by someone within the structural engineering field. This could lead to a more in depth analysis of the structure itself and perhaps a deeper understanding of when reinforced shotcrete arches should be considered a strictly concrete steel structure and when it is a interacting structure. The distinction between these two is essential for simplifying the design process of shotcrete arches.

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A

Appendix 1

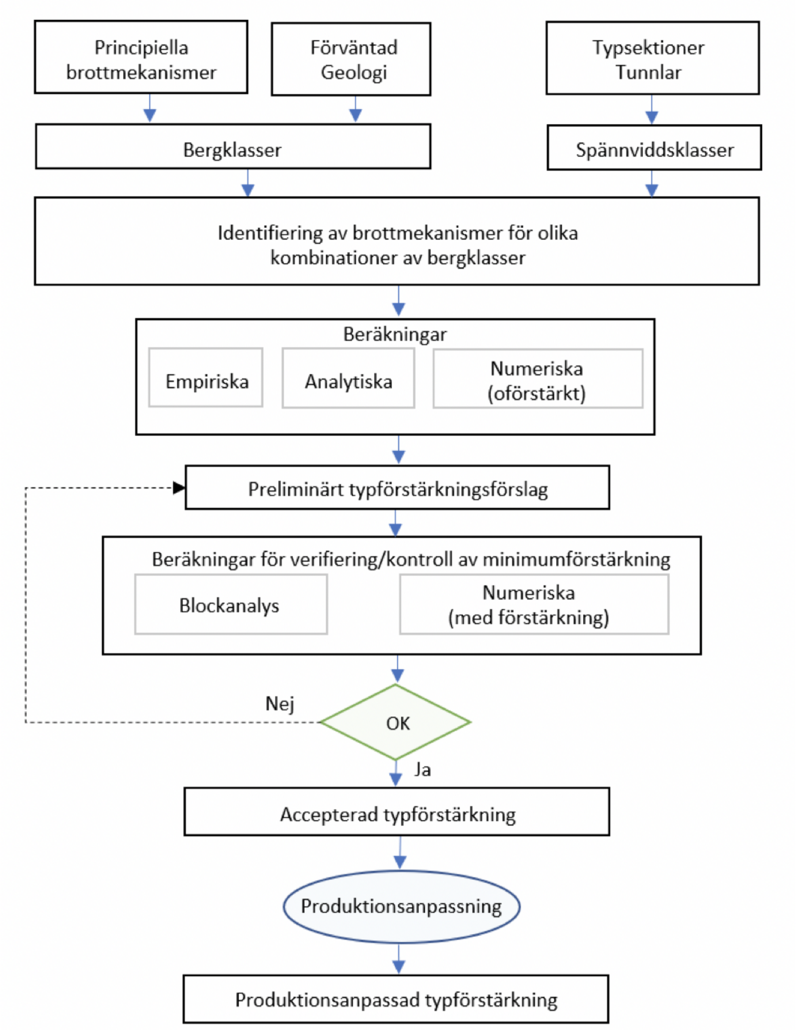

Figure A.1: *The figure shows the general design methodology of reinforced shotcrete arches designed at the West link project (Jonsson, 2020)*

B

Appendix 2

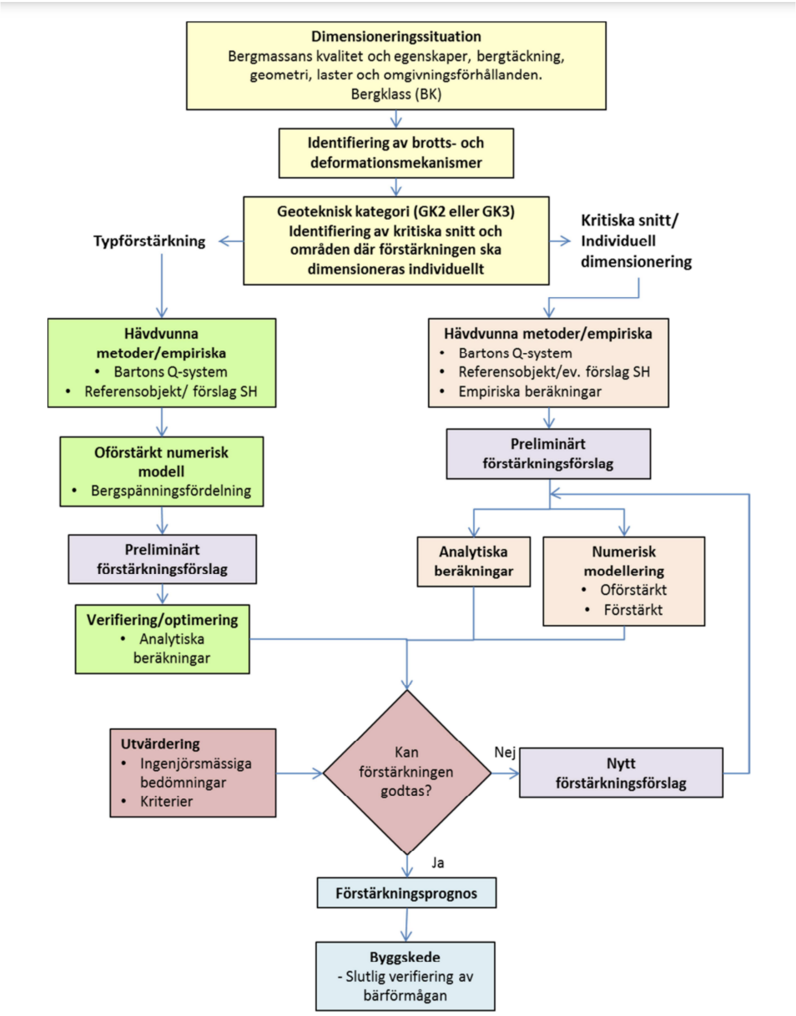

Figure B.1: *The figure shows the general design methodology of reinforced shotcrete arches designed at the E4 Stockholm bypass project (Eriksson, 2013)*

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