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Optimisation of connecting elements for shotcrete linings

Master's Thesis

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Acknowledgements

Tunnels are well known to most people! Every day we drive through them to reach our destinations quickly and conveniently. But hardly anyone knows what has to happen to make this possible. I am proud to be active in such a field and to get exciting and interesting things and places to see, as only few people do.

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Thank you and “Glück auf”!

Abstract

This master thesis is based on the preliminary work of Staudacher (2016). If a full-face excavation is not possible due to given rock conditions or large tunnel cross-sections in cyclic excavation, the shotcrete linings of the individual segments must be connected in a force-fitting manner. Staudacher developed a connecting element made of expanded metal.

The connecting element of Staudacher (2016) is reconsidered and optimised on the basis of existing problems, which were identified in the course of his master thesis. The main focus is on a stiffer construction of the connecting element as well as its installation process. In addition to the technical feasibility, the development of the element also takes into account construction management and economic aspects. The scope of this work is limited to the top heading-bench excavation and can subsequently be adapted to other excavation types.

Laboratory tests are used to investigate the removability of the concrete from the connecting element, as well as the maximum transmittable shear force. The suitability of the element, as well as an improvement compared to the version of Staudacher (2016) is confirmed.

At the end of the development phase, the connecting element is installed at the "Tunnelkette St. Kanzian" in the "Tunnel Stein" and tested regarding suitability during construction. Further optimisation with regard to the construction of the element as well as the installation process is carried out from the resulting problems in order to ensure a later impeccable function.

Since a ready for series production is to be striven for, a cost estimate is carried out.

Furthermore, optimisations to the design of a temporary top heading invert are made in order to save costs and material, as well as to facilitate the later demolition of the shotcrete lining of the invert.

Finally, it can be stated that the optimised connecting element fulfils its function very well and is suitable for the installation as a connection detail. With the use of the element in combination with the innovations of the design of the temporary top heading invert, time and money can be saved. There are advantages with regard to the statically efficiency, since the separating surface between the shotcrete lining of top heading and bench can be executed clean and even.

Kurzfassung

Die vorliegende Masterarbeit baut auf die Arbeit von Staudacher (2016) auf. Wenn aufgrund gegebener Gebirgsverhältnisse bzw. großer Tunnelquerschnitte im zyklischen Vortrieb ein Vollausbruch nicht möglich ist, müssen die Spritzbetonschalen der einzelnen Ausbrüche kraftschlüssig miteinander verbunden werden. Basierend auf einer Variantenstudie wurde von Staudacher ein Anschlusselement aus Streckmetall entwickelt.

Das Anschlusselement von Staudacher (2016) wird aufgrund vorliegender Problemstellungen neu überdacht und optimiert. Das Hauptaugenmerk wird hierbei auf eine steifere Konstruktion des Anschlusselements, sowie dessen Einbauprozess gerichtet. Bei der Entwicklung des Elements sollen neben der technischen Umsetzbarkeit auch baubetriebliche sowie bauwirtschaftliche Aspekte miteinbezogen werden. Der Umfang dieser Arbeit beschränkt sich auf den Kalotten-Strossen Vortrieb und kann in weiterer Folge auf andere Querschnittsunterteilungen adaptiert werden.

Mit Hilfe von Laborversuchen wird die Lösbarkeit des Betons vom Anschlusselement, sowie die maximal übertragbare Querkraft untersucht. Dadurch kann die Eignung des Elements, sowie eine Verbesserung in Hinblick auf die Version Staudacher (2016) bestätigt werden.

Am Ende der Entwicklungsphase wird das Anschlusselement an der „Tunnelkette St. Kanzian” im „Tunnel Stein“ eingebaut und auf seine Tauglichkeit im Baustellenbetrieb getestet. Aus sich ergebenden Problemstellungen werden weitere Optimierungen hinsichtlich der Konstruktion des Elements sowie des Einbaus durchgeführt, um eine spätere einwandfreie Funktion zu gewährleisten. Da eine serienreife Konstruktion anzustreben ist, wird eine Kostenaufstellung durchgeführt.

Des Weiteren werden Optimierungen an der Ausführung einer temporären Kalottensohle vorgenommen, um Kosten und Material einzusparen, sowie einen erleichterten Abbruch der Spritzbetonschale der Sohle zu ermöglichen.

Abschließend kann festgehalten werden, dass das optimierte Anschlusselement seine Funktion sehr gut erfüllt und für den Einbau als Anschlussdetail geeignet ist. Durch die Verwendung des Elements in Kombination mit den Neuerungen der Ausführung der temporären Kalottensohle können Zeit und Kosten eingespart werden. Es ergeben sich Vorteile in Hinblick auf die statische Wirksamkeit, da die Trennfläche zwischen Kalotte und Strosse sauber und eben ausgeführt wird.

Table of contents

List of figures

List of tables

Abbreviations

BSt...................construction steel
CE....................connecting element
M.....................moment
M10.................metric thread with nominal diameter of 10 mm
MC..................Mohr-Coulomb
N......................normal force
NATM.............New Austrian Tunnelling Method
Q......................transverse force

Symbols

w .... hole diameter of perforated metal plate [mm]
t .... hole spacing of perforated metal plate [mm]
d .... thickness of perforated metal plate [mm]
$F_{T,peak}$ .... max. normal/tensile force applied to the specimen [kN]
σ_T .... tensile stress with respect to fracture surface of specimen (∅ = 100 mm) [kN]
$\sigma_{T,peak}$ .... tensile strength with respect to fracture surface of specimen (∅ = 100 mm) [kN]
ε .... vertical strain of tension test specimen [%]
a .... length of shear box/shear area [cm]
b .... width of shear box/shear area [cm]
h .... height of shear box/shear area [cm]
$w_{h,max}$ .... predefined max. horizontal displacement [mm]
$w_{h,Fpeak}$ .... horizontal displacement at maximum horizontal force [mm]
v .... horizontal feed speed [mm/min]
t_{ST} .... testing time of shear test [sec]
F_H .... horizontal force applied to the specimen [kN]
w_h .... horizontal displacement [mm]
w_v .... vertical displacement [mm]
τ_H .... horizontal shear stress with respect to the shear area (200 x 200 mm) [N/mm^2]
σ_N .... normal stress with respect to the shear area (200 x 200 mm) [N/mm^2]
$F_{N,peak}$ .... max. normal force applied to the specimen [kN]
$F_{H,peak}$ .... max. horizontal force applied to the specimen [kN]
$F_{H,res}$ .... horizontal force applied to the specimen at end of the test [kN]
τ_{peak} .... max. horizontal shear stress (shear strength) with respect to shear area [N/mm^2]
τ_{res} .... residual horizontal shear stress with respect to shear area at end of the test [N/mm^2]
$w_{h,Fpeak}$ .... horizontal displacement at $F_{H,peak}$ [mm]
ε_h .... horizontal strain in relation to the length of the shear plane (200 mm) [%]
$\varepsilon_{h,Fpeak}$ .... horizontal strain at maximum horizontal force [%]

1 Introduction

1.1 General

This master thesis is based on the previous work of Staudacher (2016), who has already dealt with this topic in his master thesis, entitled “Anschlüsse für Arbeitsfugen bei Spritzbetonauskleidungen” in the year 2016.

The present work deals with the topic of the connection of shotcrete linings in conventional tunnelling based on the principles of the New Austrian Tunnelling Method (NATM). Frequently the excavation is carried out in the form of partial excavation. Figure 1.1 illustrates the area for which the connecting elements are to be developed. A simple, cost-efficient, but force-fitting connection of the shotcrete linings of different working steps is of great importance. The focus of this work is laid on the top heading-bench excavation as well as the top heading-bench excavation with a temporary top heading invert. The connecting element should also be applicable in combination with other excavation variants with various modifications. The connecting element is tested in practice on a tunnel construction site.

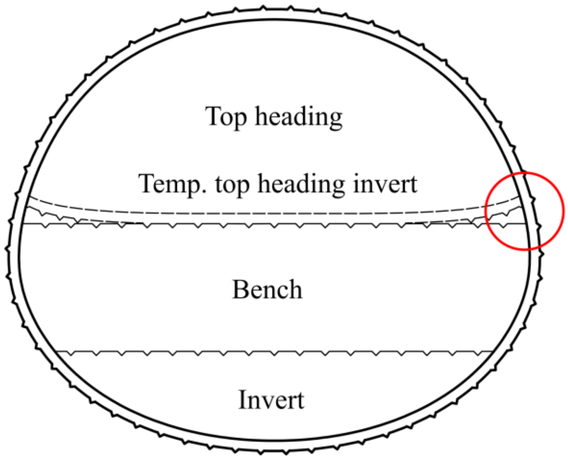


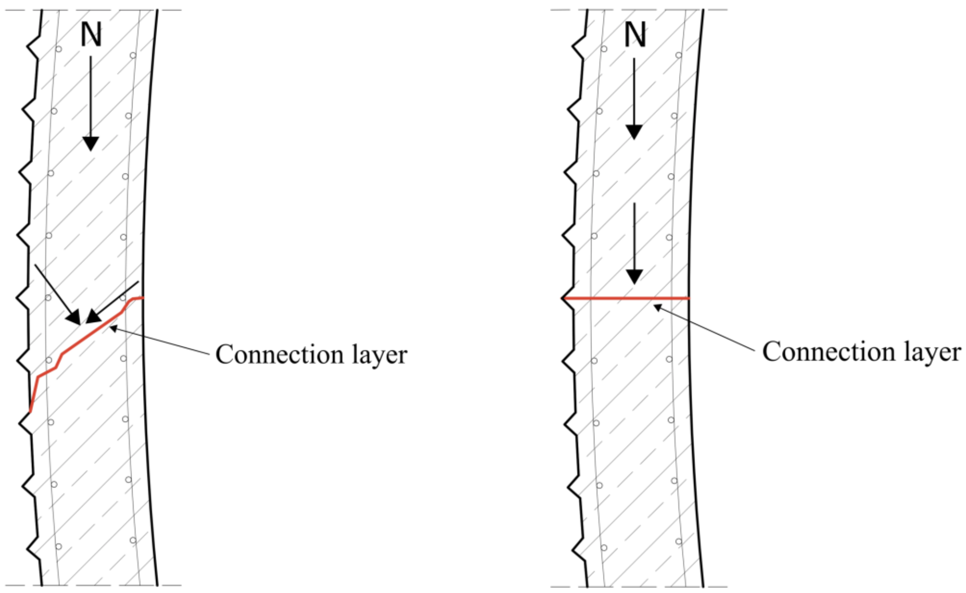
Figure 1.1: Connection detail – Top heading-bench excavation.

1.2 Requirements of the connection detail

The following requirements are necessary for the connection detail (Staudacher, 2016):

- continuous reinforcement arrangement
- planar connection joint for the transmission of normal forces
- good bonding between the shotcrete lining segments
- good removability of the shotcrete from the connecting element during the excavation of the bench

Presently, a part of the shotcrete lining of the top heading is removed mechanically after the excavation of the bench in order to expose the already incorporated connection reinforcement. This results in high time and work expenditure. Furthermore, this process often damages the connection reinforcement so that it cannot properly fulfil its requirements. An important point is the transmission of the normal forces that prevail predominantly in the shotcrete lining of the tunnel. By the mechanical removal of the concrete, an inclined and irregular joint as shown in Figure 1.2 (a) is formed. The bond of the shotcrete lining of top heading and bench is relatively small as they are produced at different times. Shotcrete residues and other remainings of the excavated material additionally reduce the bond. In a further consequence, additional transverse forces are generated in the connection joint. In order to achieve a proper transmission of the normal forces, a clean and planar connection joint should be created. An ideal execution of the connection joint is shown in Figure 1.2 (b).



(a) Force transmission with bad execution of the joint.

(b) Force transmission with good execution of the joint.

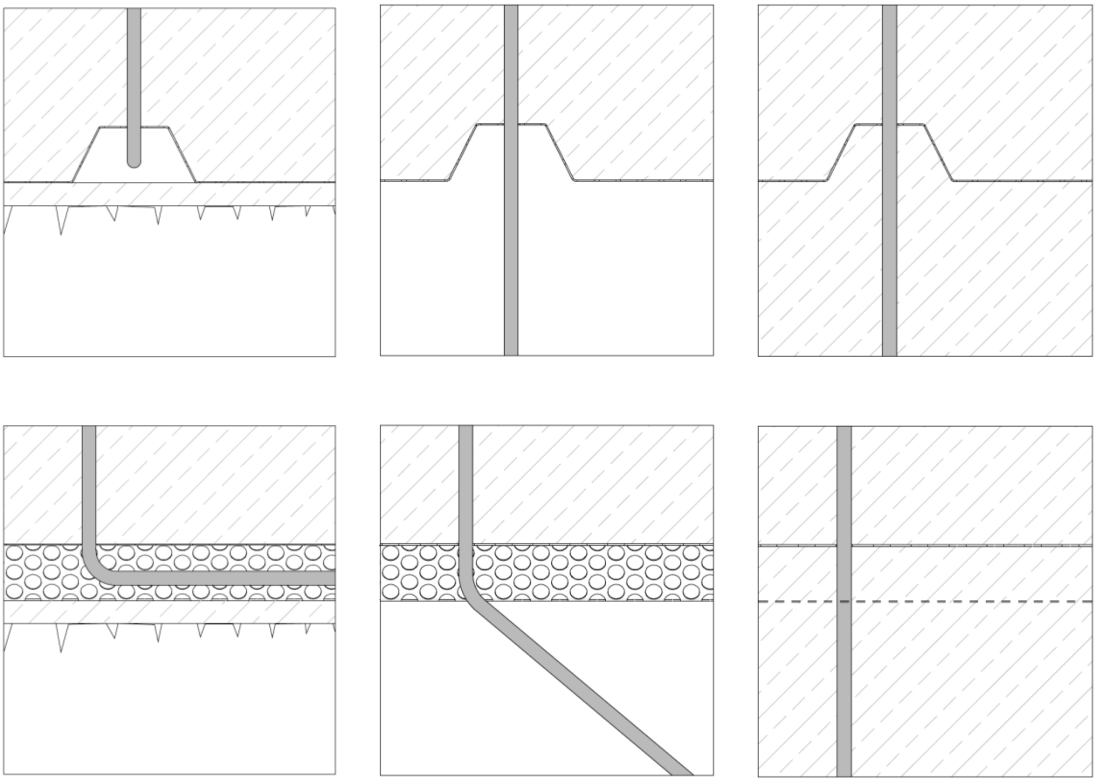
Figure 1.2: Problem of the normal force transmission in construction joints.

2 Version “Staudacher”

2.1 Concept

The development of the concept of Staudacher (2016) was carried out for a top heading-bench excavation. The system is designed to obtain a planar concrete surface of the shotcrete lining of the top heading after the excavation of the bench, in order to be able to transfer the normal forces as good as possible. For the transmission of shear forces and moments, connection reinforcement with the prescribed anchorage length is required. This is integrated in the separating layer in a way that the accessibility is guaranteed after the excavation of the bench has been made despite the spraying process.

A schematic representation of the connecting element during the construction stage is given in Figure 2.1. Figure 2.1 (a) shows the connecting element after the production of the shotcrete lining of the top heading. The connection reinforcement is bent backwards in the longitudinal direction of the tunnel into the trapezoidal recess, called shear cleat. It is of great importance that the connecting element is completely covered with shotcrete and installed as planar as possible. Due to the shear cleat, the normal forces cannot be transmitted over the entire width of the shotcrete lining. In the following working step the bench is excavated. The element is exposed on the bottom by chipping of the concrete remains. Afterwards the connection reinforcement is bent downwards, seen in Figure 2.1 (b). The final state with the already connected shotcrete linings of top heading and bench is shown in Figure 2.1 (c). The transmission of the normal forces is carried out over the entire width of the shotcrete lining. Occurring shear forces are transmitted via the connection reinforcement, the reinforcement on the cavity-side and side of the rock mass as well as the shear cleat.



(a) The connecting element is incorporated in the foot area of the top heading. Connection reinforcement is bent backwards into shear cleat.

(b) Excavation of the bench and exposure of element with later down-bending of connection reinforcement.

(c) Final state with force-fitted connection of the shotcrete linings by the connection reinforcement.

Figure 2.1: Representation of the principle of the connecting element by means of a cross section (top) and a longitudinal section (bottom) through the shotcrete lining at the transition between top heading and bench.

2.2 Development

The connecting element (CE) consists essentially of the following components:

- Main element: Expanded metal
- Connection reinforcement, longitudinal bar for bracing
- Reinforcement wire

Expanded metal

As a material for the CE Staudacher (2016) used expanded metal (Figure 2.2 (a)). Expanded metal is used as it has little weight in combination with easy workability with regard to the production and the use in construction site operation. It is already delivered to the construction site in its final shape. One advantage is that it can be variably cut off on site. Compared to other materials it is relatively cheap. Staudacher (2016) noted that in respect of the use of the CE as a separating layer, the removability of the concrete from the element, as well as the occurring rough surface, leads to advantages in the bond strength in the construction joint.

Reinforcing steel

BSt 550 reinforcing steel (Figure 2.2 (b)) with a diameter of 10 mm was used for the connection reinforcement.

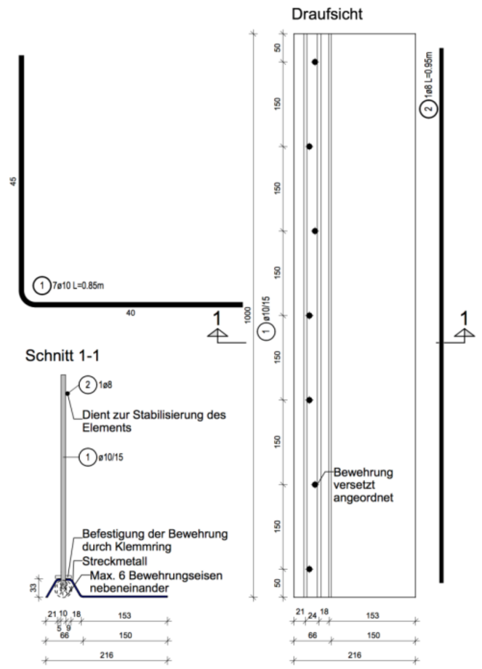
Reinforcement wire

Reinforcement wire was used to fasten the connection reinforcement to the expanded metal (Figure 2.2 (c)).

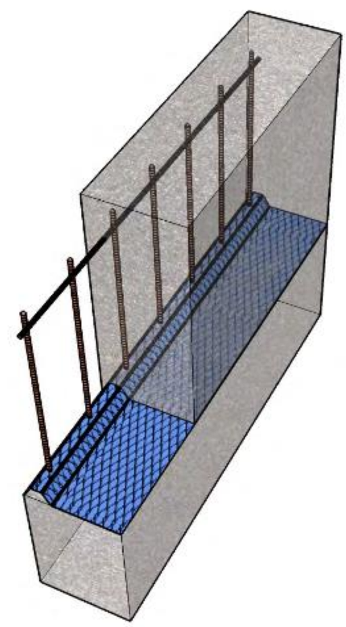
(a) Expanded metal (Mevaco GmbH, 2016). (b) Reinforcing steel BSt 550 Ø10. (c) Reinforcement wire (Kratos building products Inc., 2017).

Figure 2.2: Materials of the connecting element used by Staudacher (Staudacher, 2016).

Staudacher (2016) developed two different geometries of the CE. Version 1 (Figure 2.3) is designed for a connection without a base enlargement (so called elephant foot) of the top heading. Figure 2 shows the design for a connection in the presence of a base enlargement of the top heading. These are distinguished by the fact that at a base enlargement of the top heading, the lug of the shear cleat, which is located on the side of the rock mass is extended slightly further downwards. This helps to facilitate the removability of the concrete during the excavation of the bench (Staudacher, 2016).

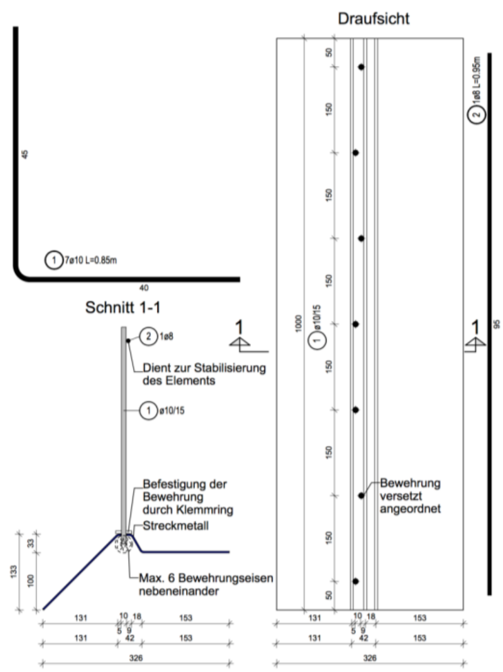


(a) Cross section and top view of the CE.

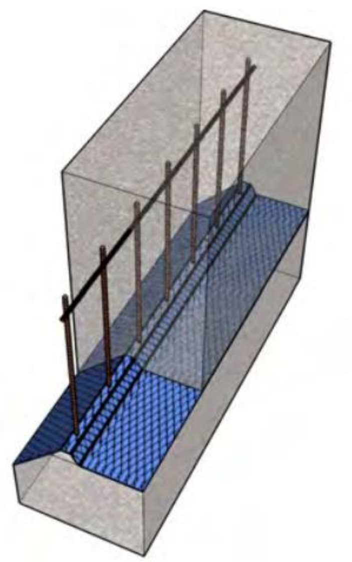


(b) 3D illustration of the CE.

Figure 2.3: Geometry of the CE "Staudacher" without elephant foot (Staudacher, 2016).



(a) Cross section and top view of the CE.



(b) 3D illustration of the CE.

Figure 2.4: Geometry of the CE "Staudacher" with elephant foot (Staudacher, 2016).

2.3 Required improvements

From the course of the master thesis of Staudacher (2016), the following issues resulted, where still potential for improvement exists.

2.3.1 Localisation of the connecting element

When the spraying of the shotcrete lining of the top heading is complete, the CE is no longer visible on the cavity-side. This results in the problem that the excavator driver cannot easily locate the CE during the subsequent excavation of the bench. This may lead to a damage of the element or even makes it unusable.

2.3.2 Stiffness of the connecting element

During the spraying of the shotcrete, damage or bending of the CE has been observed by Staudacher (2016) due to the high spraying pressure. The present CE, made of expanded metal, is not stable enough. Furthermore, damage to the element can occur easily if the transport is not carried out properly. Therefore, the construction of the CE has to be reworked again to increase the stiffness.

2.3.3 Design for a temporary top heading invert

The previous design of the connection for a temporary top heading invert is unsuitable both economically and in terms of construction (verbal information of Wulf Schubert, 11.01.2017). In the present execution of the temporary top heading invert, a superior level of concrete is used, which is extremely affecting the production costs and demolition of the invert. A solution needs to be found in order to reduce the amount of concrete and to facilitate the demolition of the shotcrete lining of the temporary invert. The connection must be carried out in a way that the construction joint is not affected by the demolition of the temporary top heading invert. In this case, the position of the connection reinforcement has to be reconsidered. Furthermore, a satisfactory force transmission should be ensured between the shotcrete lining of the top heading and the temporary top heading invert.

3 Aim of the work

The aim of the work is the optimisation of the connecting element “Staudacher” (Staudacher, 2016) and the development of an element ready for serial production.

A connecting element that ensures a simple and cost-effective connection of the shotcrete lining of top heading and bench should be developed. The requirements which are imposed on the CE in relation to static, economic, and construction management aspects are described more in detail in chapter 4.1. Two types of the CE should be developed. One for the connection of the shotcrete lining of top heading and bench and one allowing for a temporary top heading invert. Furthermore, laboratory tests are carried out with regard to the maximum shear force resistance of the element, as well as the removability of the shotcrete from the CE. Finally, the developed element shall be tested on a construction site. Adaptions resulting therefrom are included in the development. Since an element ready for series production is to be striven for, a cost estimate is carried out. To conclude this research a comparison with the previous version of Staudacher (2016) is made. Both, technical feasibility as well as economic aspects are considered.
Another point as already mentioned is the revision of the design, when using a temporary top heading invert. The new design should help to save costs, material and working time as well as facilitating the later demolition of the temporary top heading invert. Furthermore, a statically appealing solution should be maintained. The integration of the developed CE into the new design is to be striven for.

4 Optimisation

The optimisation of the connecting element is described below. In addition to the requirements for the CE, the changes in the geometry and the new materials used are shown. Subsequently, the production of a prototype is illustrated. Further adaptions of the CE and the installation process are described in the following chapters.

4.1 Requirements

The main requirements for the optimisation of the CE can be subdivided into the following areas:

- Economic requirements
- Construction management requirements
- Static requirements

4.1.1 Economic requirements

From an economic point of view, the production and installation of the CE play an important role. A further important point is the time needed for the uncovering of the CE and the bending-down of the connection reinforcement.

Production of the connecting element

- Material costs: The material costs should be kept reasonable. However, the price-performance ratio needs to be considered. If a better material is used, higher costs are incurred, but costs can be saved in other areas, such as less working time of the workers or reduction of working steps.
- Production costs: The production costs should be kept as low as possible. Therefore a simple production process is aimed for. However, one should think ahead and strive for a serial poduction of the CE to allow for a significant cost reduction.
- Production: The CE should be designed in a way that allows for prefabrication and delivery to the construction site in the finished state in order to avoid increased work of the miners or the on-site workshop.

Installation of the connecting element

In terms of cost-effectiveness the installation time as well as the time for the uncovering and the bending of the connection reinforcement plays a decisive role. The working steps should therefore be able to be carried out quickly and by only one person.

4.1.2 Construction management requirements

In the following, the most important construction management aspects regarding the production and installation of the CE are listed. These should be taken into account for the optimisation of the CE.

Requirements of the connecting element

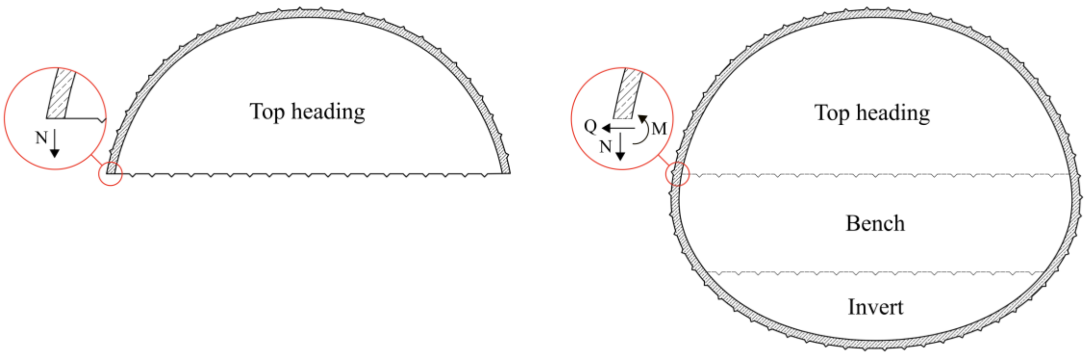
- Robustness: The CE should have the necessary robustness in order to be able to assure the suitability for on-site operation.
- Weight: An important point is that the CE can be transported to the place of use by just one person.
- Element length: In order to be able to adapt the CE to changing conditions (different round lengths), it must be possible to shorten the element with the tools available on the construction site to the desired length.
- Assembly: The assembly on the construction site shoud be feasible by just one person and without the need for additional tools.
- Storage: Due to the mostly limited storage place it is necessary to store the elements as much space saving as possible near the location of use. In this case, a stackable solution is favorable.

Requirements of the installation process

- Installation: The installation of the CE should be carried out by one person in a short time range of 5 to 10 minutes. Ideally, other works should be executed parallel to the installation process of the element.
- Handling: The installation shoud be as simple as possible without any special training of the miners.

4.1.3 Static requirements

With regard to the static requirements of a tunnel, a distinction is made between two states, which are shown in Figure 4.1 for a top heading-bench excavation. Figure 4.1 (a) shows the construction state, which persists until the excavation of the bench. In this state, only the shotcrete lining of the top heading supports the cavity of the tunnel. Since this state is only temporary, normal forces have to be transmitted mainly. The transmission of moments and transverse forces plays a subordinated role, unless a temporary top heading invert is installed. Figure 4.1 (b) illustrates the final state of the shotcrete lining, where the CE ensures a force-fitting connection of the shotcrete linings of top heading and bench. The occurring moments, normal forces and transverse forces must be transmitted. An important and general valid requirement of a working joint is that no weakening of the shotcrete lining by the construction joint may occur.



(a) Construction state.

(b) Final state.

Figure 4.1: Decisive static requirements for the respective state.

4.2 New design

As already mentioned, two different versions are designed during the development of the CE. However, it is desirable to use the same CE for both tunnel designs. Material, geometry, function as well as the installation on the construction site are included in the development.

4.2.1 Connecting element for top heading-bench excavation

The CE consists of the following components:

- Main element (= separating layer) made of a prefabricated perforated metal plate that is delivered to the construction site in its final shape.
- Connection reinforcement and longitudinal bar for bracing.
- Reinforcement wire for fixing the connection reinforcement.
- Square timber for creating a notch in the shotcrete lining.
- EPS to prevent the connection reinforcement from being covered with shotcrete.

4.2.2 Material

Perforated metal plate

Perforated metal plates with circular holes with an inclined arrangement have proven to be the most suitable material for the CE. Tension tests (see chapter 6.1) have shown that the hole diameter is not critical. The hole diameter of the CE can thus be chosen due to the diameter of the required reinforcement bars. Due to the given boundary conditions, the perforated metal plate of type R12T15.55 proved to be the most appropriate (Figure 4.2 (a)). The respective data can be found in Table 4.1. The advantages of the perforated metal plate are mainly reflected in the lower weight as well as in a much higher stiffness compared to the previously used material. The costs of the perforated metal plate are about 20 % lower compared to the expanded metal. The use of such a CE results in further cost savings in other areas. The exact costs for a single CE can be seen in chapter 8. With regard to the function as a separating element, the removability of the concrete of the CE (more in detail in chapter 6.1), as well as the resulting rough surface, leads to advantages in the bond strength in the construction joint. The CE made of the perforated metal plate can be cut to the required length with the tools present on the construction site.

Table 4.1: Dimensions of the perforated metal plate type R12T15.55.

Type	Hole diameter w [mm]	Hole spacing t [mm]	Free cross section [%]	Number of holes per m^2 [-]	Thickness d [mm]
R12T15.55	12.00	15.55	54.00	8019	1.00

Reinforcing steel

BSt 550, Ø10 is used for the connection reinforcement, shown in Figure 4.2 (b). The length is set to the minimum anchorage length, used at the Tunnel Stein. If reinforcement bars with larger nominal diameter are required, it is necessary to adapt the CE either by widening the holes or using a perforated metal plate with a larger hole diameter.

Reinforcement wire

Reinforcement wire is used to fasten the connection reinforcement to the CE (Figure 4.2 (c)).

Square timber

A square timber (Figure 4.2 (d)) is attached at the cavity-side of the CE during spraying of the shotcrete and removed before the excavation of the bench. This leads to a continuous and clearly visible notch in the shotcrete lining of the top heading. The excavation bucket can be positioned in the notch. When a temporary top heading invert is required, the generated notch allows to bend down the connection reinforcement easily without damaging the shotcrete lining of the top heading (Figure 4.9). Square timber with a cross-section of 10 x 10 cm (used at Tunnel Stein) is cut into the same length as the CE. The application of a wooden closing strip proved to be cheap and allows for an easy handling. Due to the notch produced, there are further advantages with regard to the production and demolition of the shotcrete lining when using a temporary top heading invert.

EPS

An EPS strip (Figure 4.2 (e)) is attached on the bottom side of the shear cleat to prevent the connection reinforcement from being covered with shotcrete.

(a) Perforated metal plate of type R12T15.55.

(b) Reinforcing steel BSt 550 Ø10.

(c) Reinforcement wire (Kratos building products Inc., 2017).

(d) Square timber 10x10 cm (OBI E-Commerce GmbH, 2017).

(e) EPS (Coop Bau+Hobby, 2017).

Figure 4.2: Materials of the connecting element version “Wenger”.

4.2.3 Geometry

The geometry of the CE depends on:

- The thickness of the shotcrete lining,
- the round length or distance between two lattice girders,
- and the surrounding rock mass.

An adaption of the element to site-specific conditions is easily possible. The illustrated geometry of the CE is related to a thickness of the shotcrete lining of 30 cm and a round length of 1.30 m. The basic form of the version “Staudacher” (Staudacher, 2016) was preserved, but adjustments were necessary to allow for a more suitable element. A fundamental difference is the lug, which is bent over 90°, on the cavity-side of the CE. This lug helps to increase the stiffness of the element and to position the used square timber. It also serves as a predetermined breaking point during demolition of the shotcrete lining of the temporary top heading invert. Furthermore, small changes in the dimensions were carried out. The dimensions have been adapted to the position of the used lattice girder of type 95/20/30. The trapezoidal shear cleat must be located at the level of the chord of the lattice girder on the side of the rock mass in order to fix the connection reinforcement to the previously installed reinforcement steel mesh.

When using expanded metal, the required connection reinforcement could simply be inserted through the metal at any point of the element. However, when the perforated metal plate is used, this is limited by the predetermined hole arrangement. In order to place all the reinforcement bars in the shear cleat, they must be installed with a slight offset into the CE. Therefore, the upper length of the shear cleat has been increased to provide at least two to three rows of holes for the offset of the connection reinforcement.

The remaining dimensions were selected on the basis of the new installation situation and the used square timber. The 90°-lug is positioned approximately 7 cm behind the cavity-side chord of the lattice girder due to the width of 10 cm of the used square timber. The new installation variant (see Appendix A and B) allows using the same element for a design with a base enlargement (elephant foot) of the top heading.

The element is produced with a standard length of 1.00 m. For shorter round lengths, the element is shortened using a disc grinder at the tunnel face. For larger round lengths two elements can be overlapped. The optimised CE with all its components is shown in Figure 4.3. The assembly of the CE is illustrated in Figure 4.4. The dimensions of the used connection reinforcement are shown in Figure 4.3. The bent bars (number 2) serve for the connection of the shotcrete linings of top heading and bench. They are already installed in advance in the CE. The longitudinal bar (number 3) is used to stabilise the element and is fixed to the bent bars (number 2) with reinforcement wire.

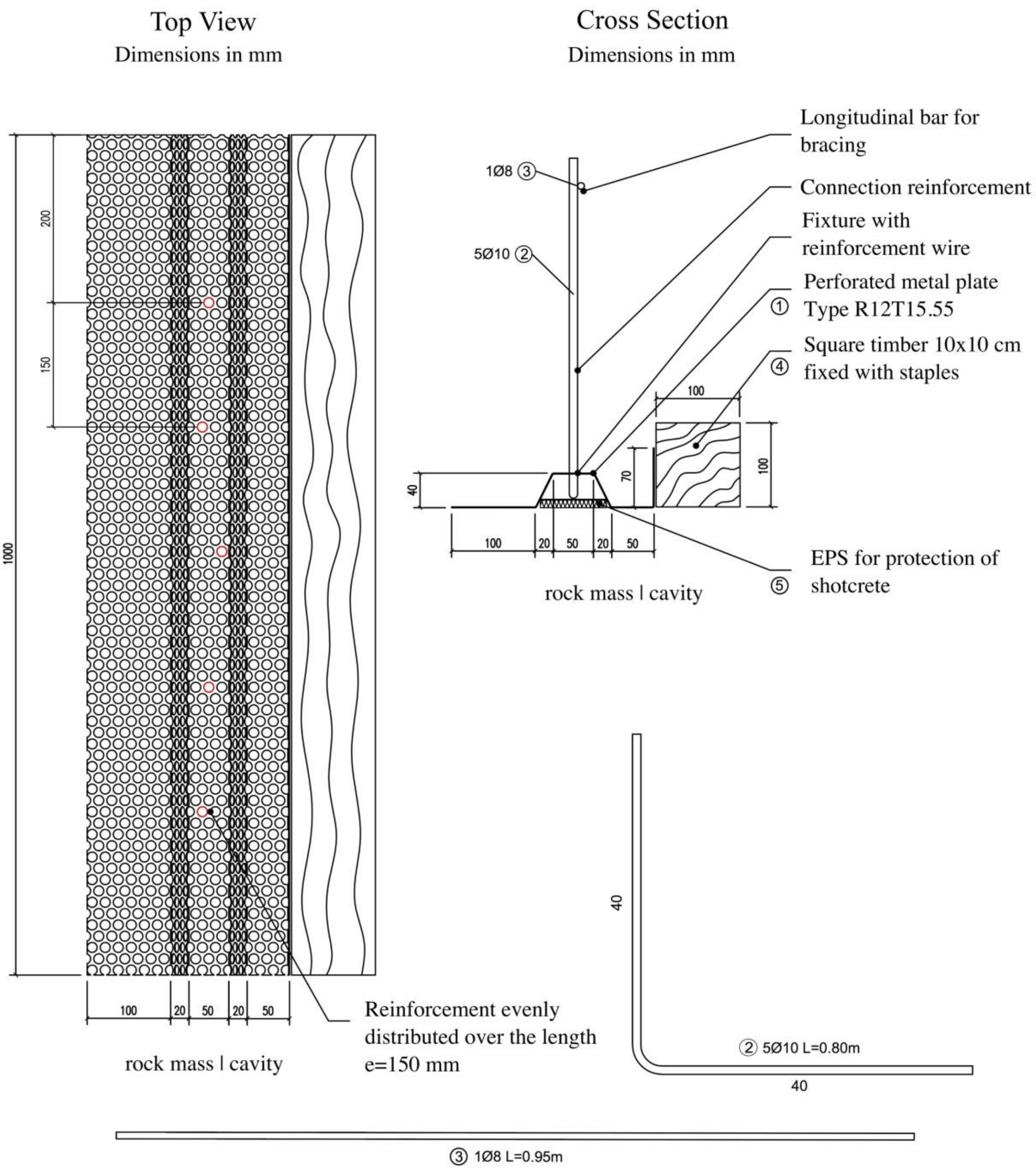
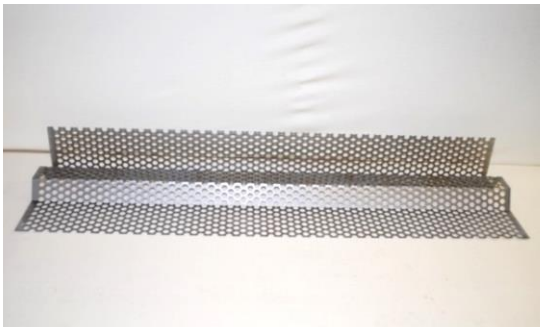


Figure 4.3: Optimised connecting element showing all components.

4.2.4 Assembly of the connecting element

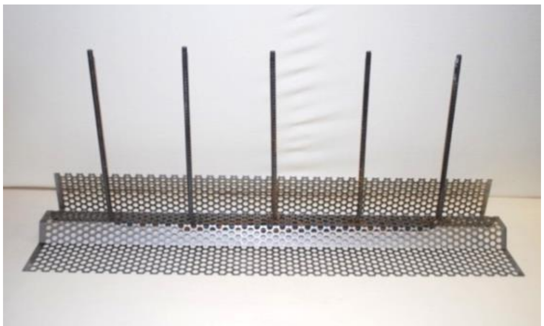
The connection reinforcement is already delivered in it bent state. Installation within the CE can be done by one miner. The individual installation steps are shown in Figure 4.4.



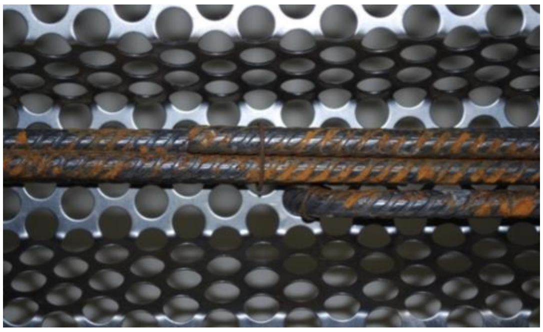
(a) Prefabricated perforated metal plate of type R12T15.55 in the bended state.

(b) Connection reinforcement is inserted through the holes of the perforated metal plate.

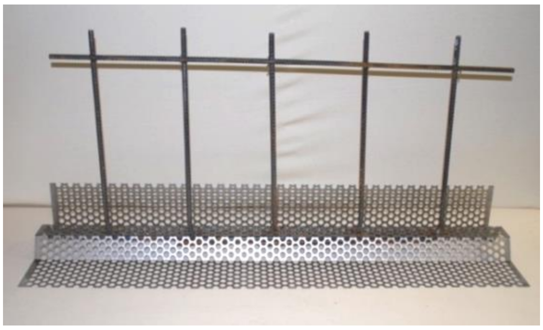
(c) Connection reinforcement is installed with offset to each other and is fixed with reinforcement wire.



(d) Connecting element with completely installed connection reinforcement.



(e) Additional attachment of the connection reinforcement using reinforcement wire.



(f) Final connecting element with bracing longitudinal reinforcement bar.

Figure 4.4: Assembly of the connecting element – Working steps.

In the final step the square timber is fixed to the vertical lug of the CE (Figure 4.5) and an EPS strip with the required dimensions is attached to the bottom side of the shear cleat.

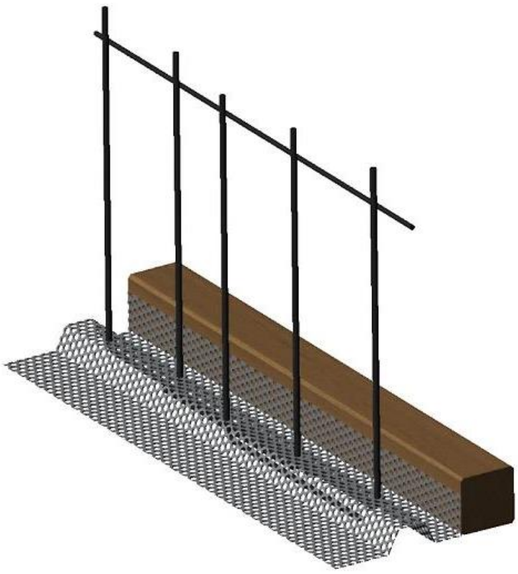
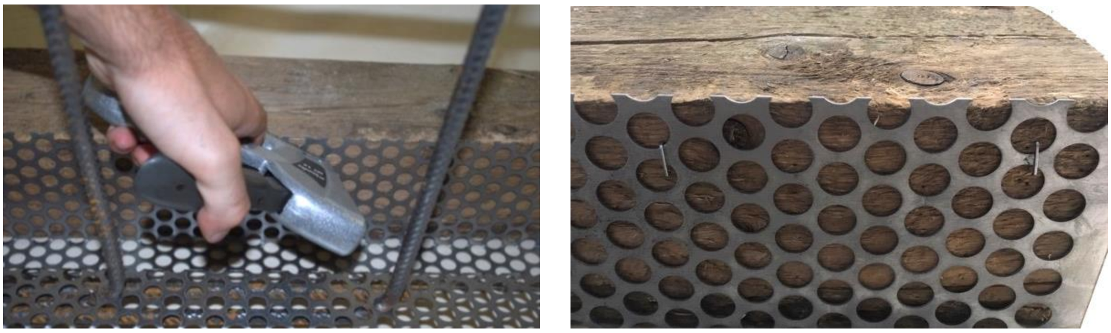


Figure 4.5: Connecting element with fixed square timber.

The removal of the square timber by hand is intended to protect both the CE and the square timber itself. For an easy removal a cramp (DIN 7961, Type A) is inserted into the square timber prior to the installation. The cramp of DIN 7961 Type A (Figure 4.6) consists of a 16 mm thick round steel with a length of 300 mm and a height of 90 mm.

Figure 4.6: Cramp according to DIN 7961 Type A (Dönges GmbH & Co. KG, 2017).

The square timber was initially attached to the CE using reinforcement wire. During the on-site tests, it was observed that the reinforcement wire was too strong. When the square timber was removed, the vertical lug of the CE in some cases was bent down. Therefore, the fixing of the square timber should be performed with a simple stapler (Figure 4.7). Care must be taken that the square timber can be removed easily when necessary. The square timber can thus be firmly fixed to the CE for transportation, but on the other hand it can be detached very easily.



(a) Fastening of square timber with stapler. (b) Staples are evenly distributed over length.

Figure 4.7: Fastening of the square timber with staples to the connecting element.

The assembly of the CE is relatively easy and takes about 6 to 7 minutes per element. All necessary tools are available on the construction site. Furthermore, enough space is available to store the elements without problems.

4.2.5 Application of the square timber

The individual steps of the application of the square timber are explained for a top heading-bench excavation with a temporary top heading invert. The specific installation steps are illustrated in red (Figure 4.8 and Figure 4.9).

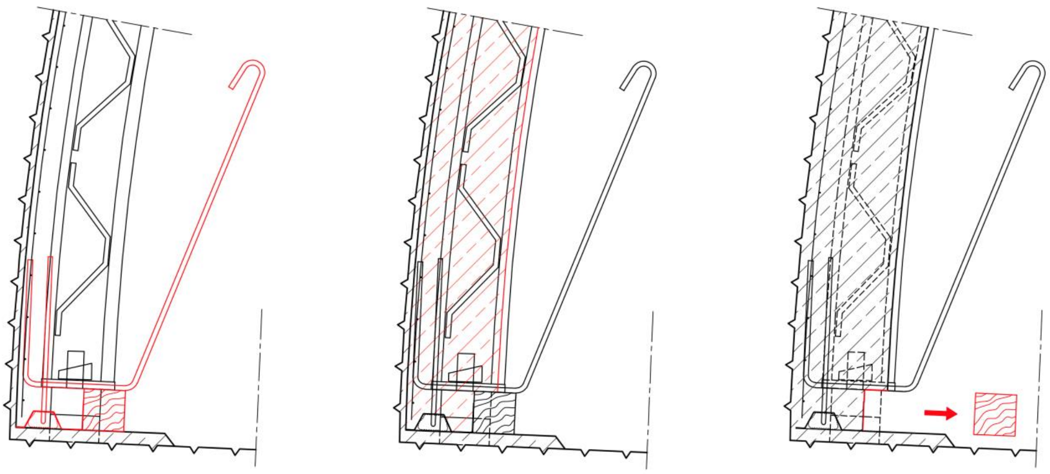
(a) Positioning of the connecting element and installation of connection reinforcement
The CE with the fixed square timber is placed on the previously sprayed shotcrete bank. The upper end of the square timber should be approximately at the level of the bottom side of the base plate of the lattice girder. The reinforcement bars for the connection of the temporary invert are positioned directly on the top of the square timber and are fixed to the outer reinforcement steel mesh.

(b) Spraying of the shotcrete lining
In the next step the first layer of the shotcrete lining of the top heading is sprayed. The square timber should not be covered with concrete and should protrude from the shotcrete lining.

(c) Removal of square timber
In the final step the square timber is removed from the shotcrete lining thus creating a notch in the concrete. Due to the generated notch the CE can be located easily. Subsequently, the excavator driver can start directly in the notch with the excavation of the bench.

(d) Excavation of temporary top heading invert area and bending down of reinforcement
After the square timber has been removed from the shotcrete lining of the top heading, the temporary top heading invert is excavated (Figure 4.9). The excavator driver can place the excavation bucket directly in the produced notch. The notch allows an easy downward bending of the connection

reinforcement for the shotcrete lining of the temporary top heading invert, as more free space is created. As a further consequence, damage to the existing shotcrete lining of the top heading can be prevented.



(a) (b) (c)

Figure 4.8: Application of the square timber shown for a top heading-bench excavation with temporary top heading invert (step 1–3).

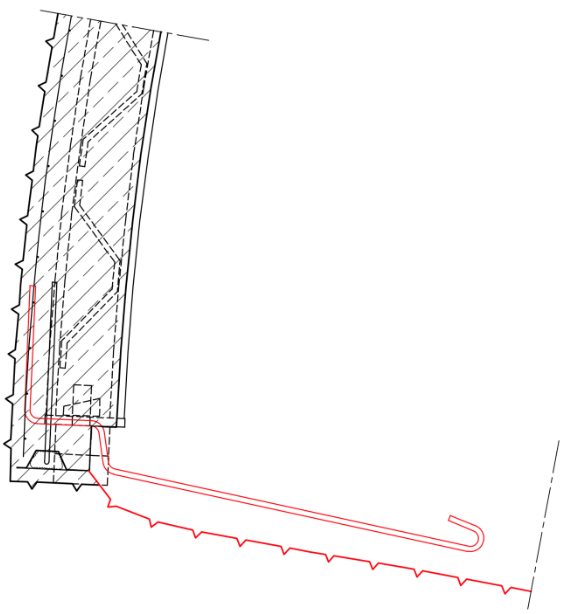
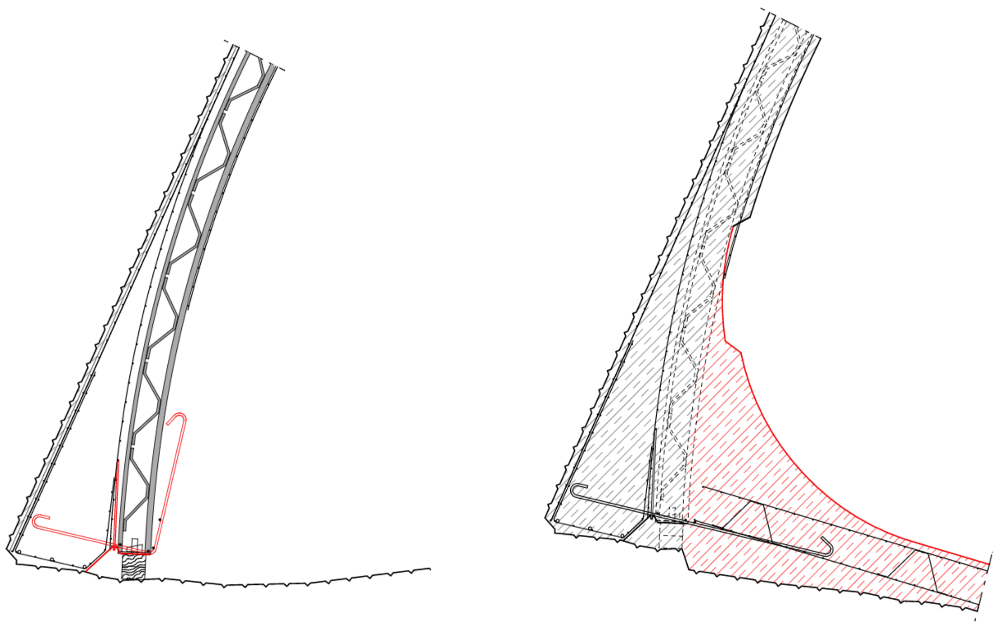


Figure 4.9: Bending down the connection reinforcement for the temporary top heading invert (step 4).

5 Improvements to the execution of a temporary top heading invert

As already mentioned in chapter 2.3.3, the design of the temporary top heading invert in some cases is not ideally solved (verbal information of Wulf Schubert, 11.01.2017). Since the execution of the temporary top heading invert is very project-specific, the optimisation in this work is limited to the design used at Tunnel Stein, shown in Figure 5.1. As can be seen in Figure 5.1 (b) the temporary top heading invert is directly connected to the pre-existing shotcrete lining. During the subsequent demolition of the invert this connection causes damage to the shotcrete lining of the top heading. A solution for a damage-free demolition of the temporary top heading invert must be found. In the version of Staudacher (2016) the CE is fixed directly to the connection reinforcement of the temporary invert. During the subsequent bending down of the connection reinforcement, damage or detachment of the CE occurred. Therefore, the position of the CE or the connection reinforcement of the temporary invert is reconsidered.



(a) Installation of the connection reinforcement for the temporary top heading invert (red).

(b) Completed temporary top heading invert (red).

Figure 5.1: Present execution of the temporary top heading invert used at Tunnel Stein (Staudacher, 2016).

5.1 Requirements

For the development of the new concept of the connection to the temporary top heading invert special attention was paid to the following aspects:

- Integration of the developed CE (version “Wenger”),
- Reduction of shotcrete wastage,
- Prevention of damage of the construction joint during demolition of the temporary invert,
- Prevention of damage to the shotcrete lining of the top heading,
- Easy demolition of the temporary top heading invert,
- Statisfactory force transmittion (normal force, moment and shear force).

A solution for an easy combination with the developed CE without having a considerable amount of work time and material should be found. Together with the company 3G Geotechnik Gruppe Graz ZT GmbH, Graz (Austria) improvements to the basic design of the temporary top heading invert were developed. As an ideal solution, the already developed CE can be integrated into the design without any adaptions.

5.2 New design for the temporary top heading invert

For the new design of the temporary top heading invert, various modifications as shown in Figure 5.2 were necessary and are described in detail in the following section.

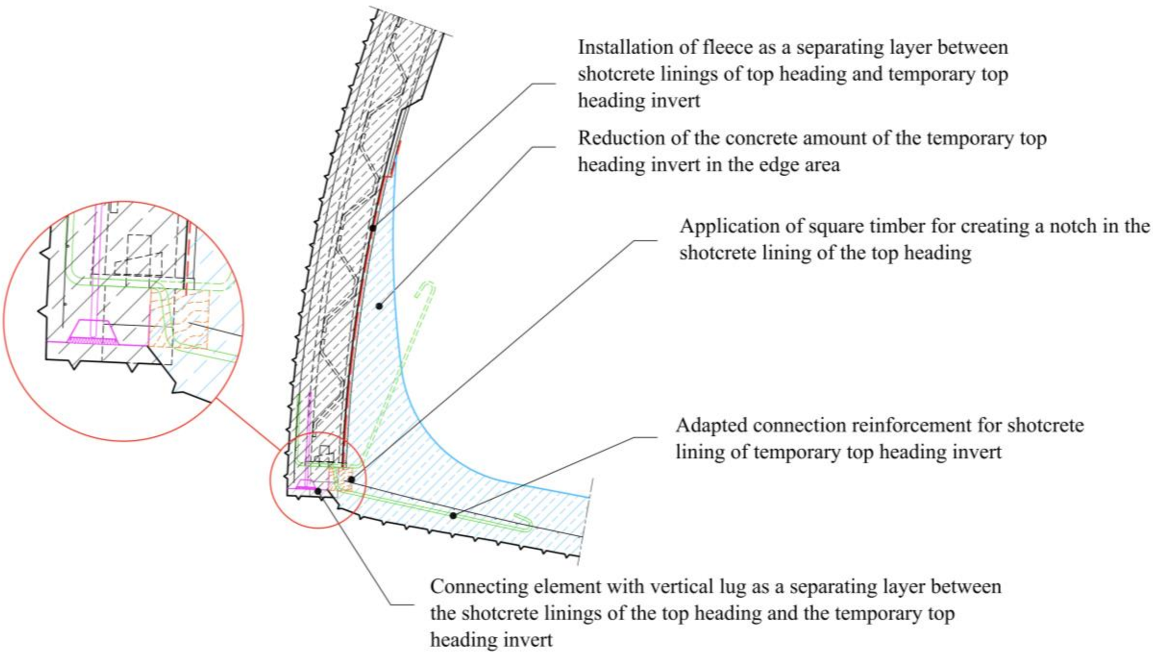


Figure 5.2: New design for the temporary top heading invert.

5.2.1 Connecting element

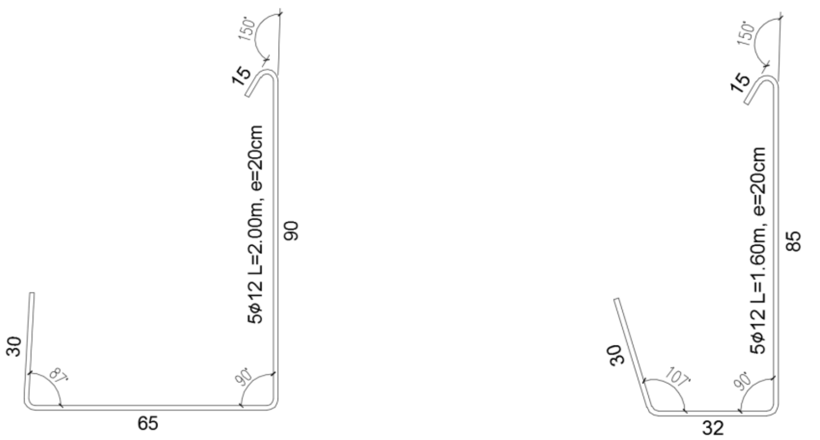
The geometry of the CE for a top heading-bench excavation is identical for a design with or without a temporary top heading invert. The CE is placed about 10 cm below the base plate of the lattice girder (the CE of Staudacher (2016) was placed at the height of the base plate). Due to the vertical lug of the CE, an additional separating layer is created between the shotcrete lining of the top heading and the temporary top heading invert. This leads to an easier demolition of the shotcrete lining of the temporary top heading invert.

5.2.2 Square timber for creating a notch in the shotcrete lining

The application as well as the advantages of the square timber are described in chapter 4.2. The square timber is illustrated with dashed lines in Figure 5.2, as it is removed again before the excavation of the temporary top heading invert area.

5.2.3 Connection reinforcement of temporary invert

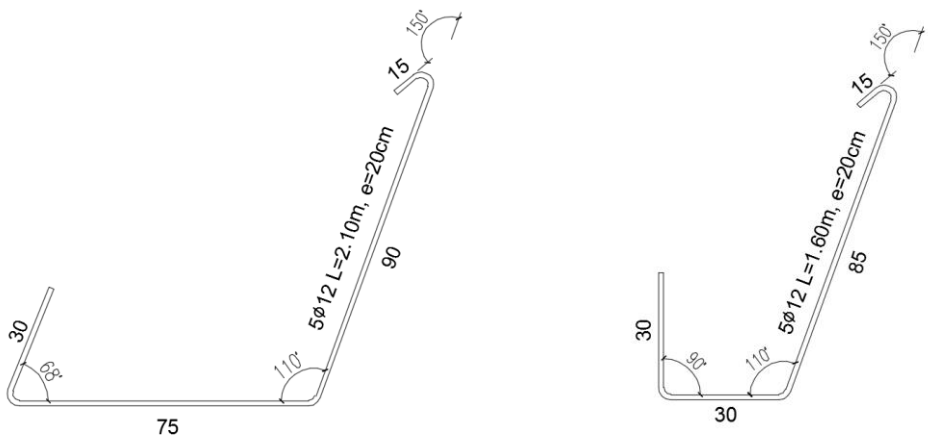
For the connection of the temporary top heading invert and the shotcrete lining of the top heading the connection reinforcement shown in Figure 6.3 was used at Tunnel Stein. Figure 5.4 shows the adapted version of the connection reinforcement. The adaptions result from the new execution of the installation. These are required to ensure sufficient distance of the protruding steel bars from the shotcrete lining to be produced to prevent a covering of the steel bars with shotcrete. The connection reinforcement is arranged above the CE in order to avoid complications in the bending down of the reinforcement bars as well as in the later demolition of the temporary invert. It is positioned horizontally on top of the square timber. Five pieces are installed per round (1.30 m) at a distance of 20 cm.



(a) With base enlargement of the top heading.

(b) Without base enlargement of the top heading.

Figure 5.3: Connection reinforcement of the temporary top heading invert used at Tunnel Stein [dimensions in cm].



(a) With base enlargement of the top heading.

(b) Without base enlargement of the top heading.

Figure 5.4: Adapted connection reinforcement of the temporary top heading invert [dimensions in cm].

5.2.4 Fleece as a separating layer

A fleece is included as a separating layer in order to allow for an easier demolition of the shotcrete lining of the temporary top heading invert, as well as a protection for the shotcrete lining of the top heading. The fleece is fixed prior to spraying of the invert on the cavity-side of the existing shotcrete lining of the top heading. The dimensions of the fleece are 1 m in height and correspond to the length of about four rounds. The data of the fleece can be found in Appendix C, the results of the shear tests can be found in chapter 6. The used fleece is perfectly suited for tunnelling due to its high mechanical protective effect and its high transmissivity and is crucial for the stability of the structures (Dapek Dach- und Abdichtungstechnik GmbH, 2017).

5.2.5 Shotcrete lining of temporary invert

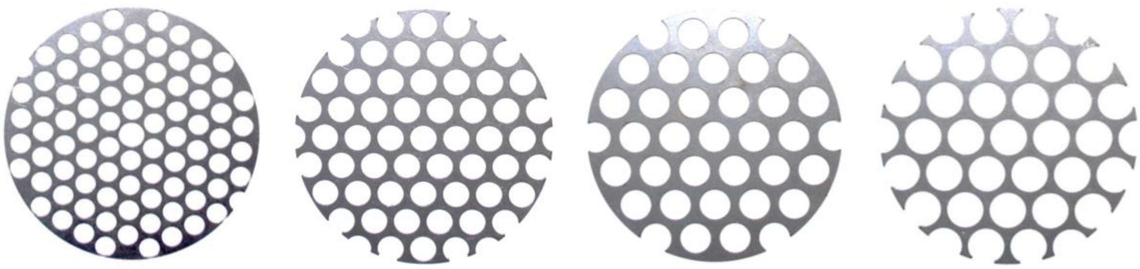
In the production of the temporary top heading invert wastage of shotcrete should be kept to a minimum. The shotcrete should not extend over the upper end of the fleece. Because the invert is only a temporary construction and it is destroyed again after a few weeks, the excessive amount of concrete in the edge area of the invert is not mandatory since the stability is sufficient for this time period (verbal information of Peter Sellner, 18.05.2017). However, this must be taken into account in the design of the tunnel and a proof according to Eurocode has to be carried out. Furthermore, an easier demolition of the shotcrete lining of the temporary top heading invert is achieved and saves time and costs.

6 Laboratory tests

Based on performed laboratory tests, the maximum transmissible shear force as well as the removability of the shotcrete from the perforated metal plate was investigated. The test results are compared with the results obtained by Staudacher (2016) to investigate if the behaviour changes.

6.1 Tension tests

Tension tests were performed in order to investigate the removability of shotcrete from the CE. Therefore, various perforated metal plates with different hole diameters were embedded in concrete specimen. As the use of shotcrete was not feasible for the performed tests concrete of type C16/20 (preliminary test) and C25/30 (series 1 and 2) was used. As shown in Figure 6.1 four different plate types were tested. Focus was more laid to the shape of the fracture surface of the concrete than on the occurring forces. A total of three series, consisting of two tests for the preliminary tests and series 1 and one test for series 2, were performed. The preliminary tests were carried out in order to preclude inappropriate hole diameters of the perforated metal plates in advance and are not described in detail. The plates had a diameter of 100 mm and a thickness of 1.5 mm for the preliminary tests and a thickness of 1.0 mm for series 1 and 2. For the CE, a thickness of 1.0 mm was chosen since the stiffness is sufficient. All metal plates consist of a mild steel of type 1.03302B. The arrangement of the holes is shown in Figure 6.2. The dimension of the perforated plates are listed in Table 6.1, a datasheet can be found in Appendix D. Table 6.2 shows the types of the perforated metal plates used in the individual test series.



(a) R8T10. (b) R10T12.7. (c) R12T15.55. (d) R14T16.5.

Figure 6.1: Perforated metal plates used for the direct tension tests with declaration of the type.

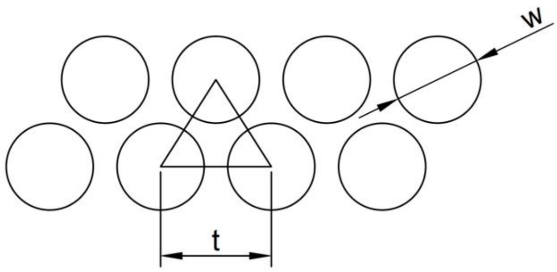


Figure 6.2: Arrangement of the holes.

Table 6.1: Dimensions of the perforated metal plates.

Type	Hole diameter w [mm]	Hole spacing t [mm]	Free cross section [%]	Number of holes per m^2 [-]
R8T10	8.00	10.00	58.05	18042
R10T12.7	10.00	12.70	56.20	11547
R12T15.55	12.00	15.55	54.00	8019
R14T16.5	14.00	16.50	65.00	5891

Table 6.2: Overview of the used plate types in each series.

Type	Preliminary test	Series 1.1/1.2	Series 2.1
R8T10	X		
R10T12.7	X	X	X
R12T15.55	X	X	X
R14T16.5	X		

6.1.1 Test configuration and test procedure

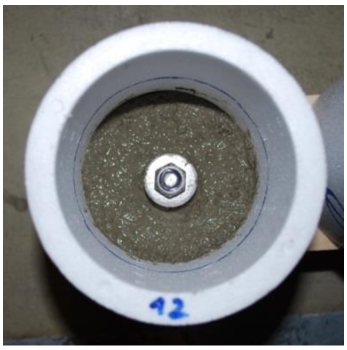
The removability of the concrete was determined by direct tensile tests using a servo-hydraulic test apparatus. Embedded threaded rods allowed force transfer into the specimen. The test setup is visualized in Figure 6.3. For all tests, the tensile force (F_N) was increased at a constant rate (v) 0.75 mm/min until the specimen failed. The tensile force (F_N) and the respective displacements were measured and evaluated. It is denoted that the test configuration shown in Figure 8.4 was identical for all test series. Only the dimensions of the specimen were changed slightly.

Figure 6.3: Test configuration of tension test.

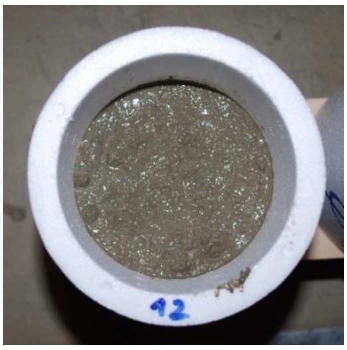
6.1.1 Production of the specimen of series 1 and 2

Concrete with strength class C25/30 was used for test series 1.1 and 1.2. The individual preparation steps are described in Figure 6.4. For the application of the tensile force (F_N) threaded rods (M10) were incorporated at both ends of the specimen. Additional washers were used to increase the pull-out resistance. The specimens were concreted in two stages (upper and lower half). The perforated metal plate was installed over the full cross-section in the middle of the specimen. After the concreting of each layer, the specimens were compacted for 3 minutes at a frequency of 40 turns per minute on a vibrating table. To take into account different advance rates on site, the tension tests were performed after 12 (series 1.1, series 2.1) and 8 days of curing (series 1.2). An example of a finished specimen is shown in Figure 6.5.

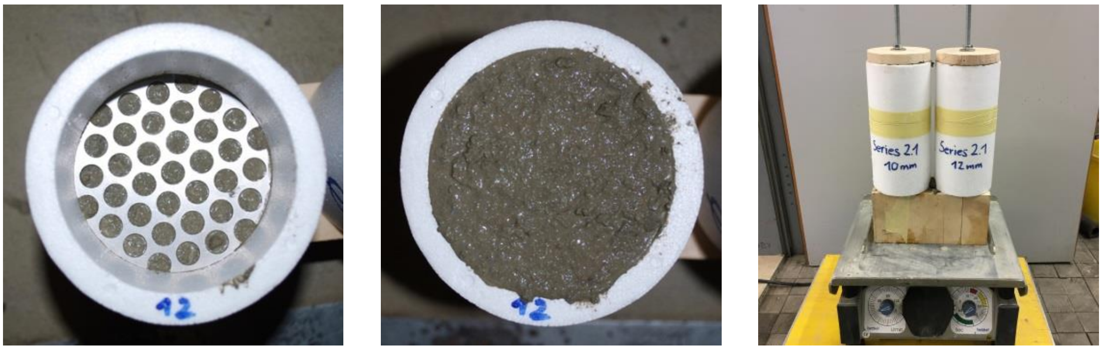
(a) Formwork with threaded rod in the lower half.



(b) Layered filling of the formwork and subsequent compaction.



(c) Filling of the formwork with concrete up to the middle of the formwork.



(d) Placement of the perforated metal plate.

(e) Filling the form work up to the top edge.

(f) Compacting of the specimen on a vibrating table.

Figure 6.4: Preparation of the specimen of series 2.1.

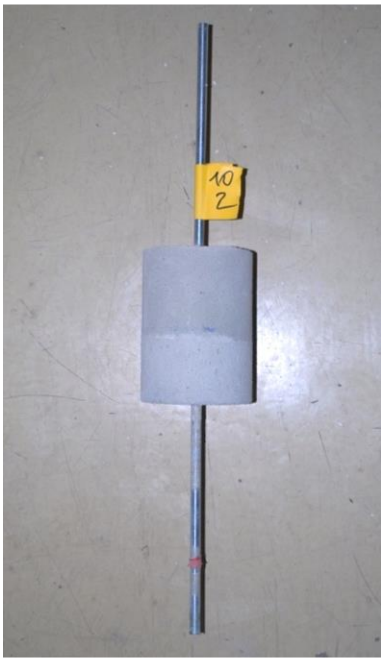
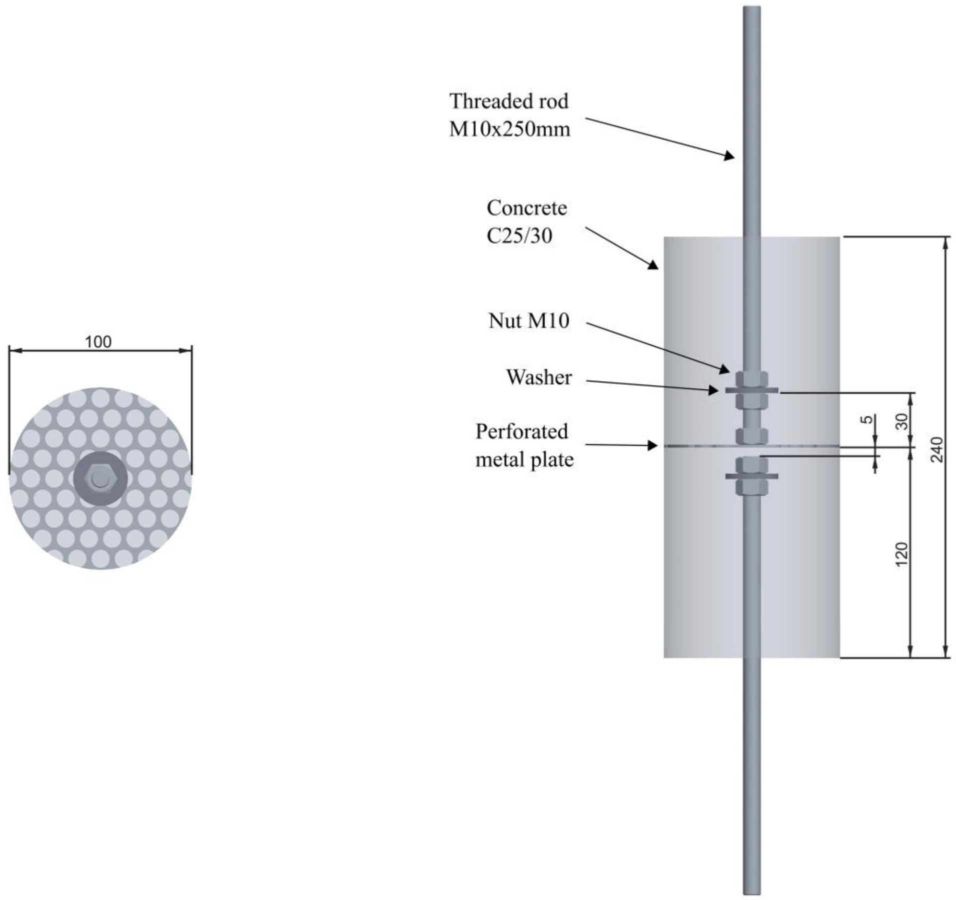


Figure 6.5: Example of a specimen of the preliminary series.

6.1.1 Series 1.1 and 1.2

For series 1.1 and 1.2 only the metal plates R10T12.7 and R12T15.55 were used. In order to achieve a fracture in the area of the perforated plate the height of the specimen was increased from 140 mm to 240 mm and the upper threaded rod was welded to the perforated metal plate to simulate the integrated connection reinforcement in the CE. Furthermore, the distance between the lower threaded rod and the perforated metal plate was reduced from 35 mm to 5 mm. The used concrete was increased to strength class C25/30 which is also comparable to shotcrete used on most tunnel construction sites. The detailed geometry of the specimen for series 2.1 and 2.2 is shown in Figure 6.6.

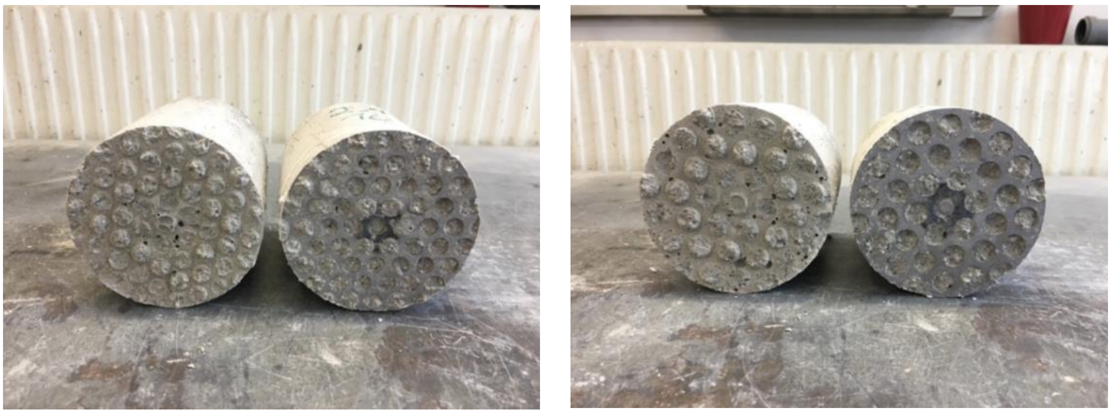


(a) Top view of the specimen.

(b) Front view of the specimen.

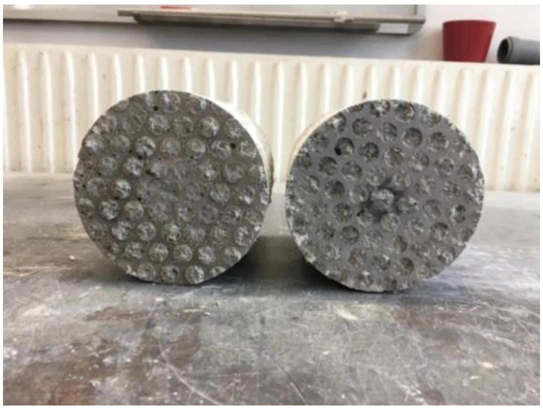
Figure 6.6: Geometry of the specimen of series 1.1 and 1.2.

As seen in Figure 6.7 all specimen of series 1.1 and 1.2 fractured along the intended surface at the perforated metal plates. The measured tensile strength ($\sigma_{T,peak}$) yielded a value of 1.15 MPa with a hole diameter of the perforated metal plate of 10 mm. A value of 1.24 MPa was reached with a hole diameter of 12 mm (Table 6.3). The results only show a minor difference in the capacity of the different perforated metal plates of roughly 10 %.

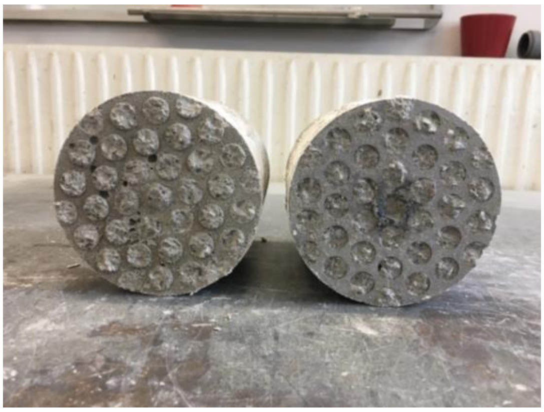


(a) Series 1.1: R10T12.7.

(b) Series 1.1: R12T15.55.



(c) Series 1.2: R10T12.7.



(d) Series 1.2: R12T15.55.

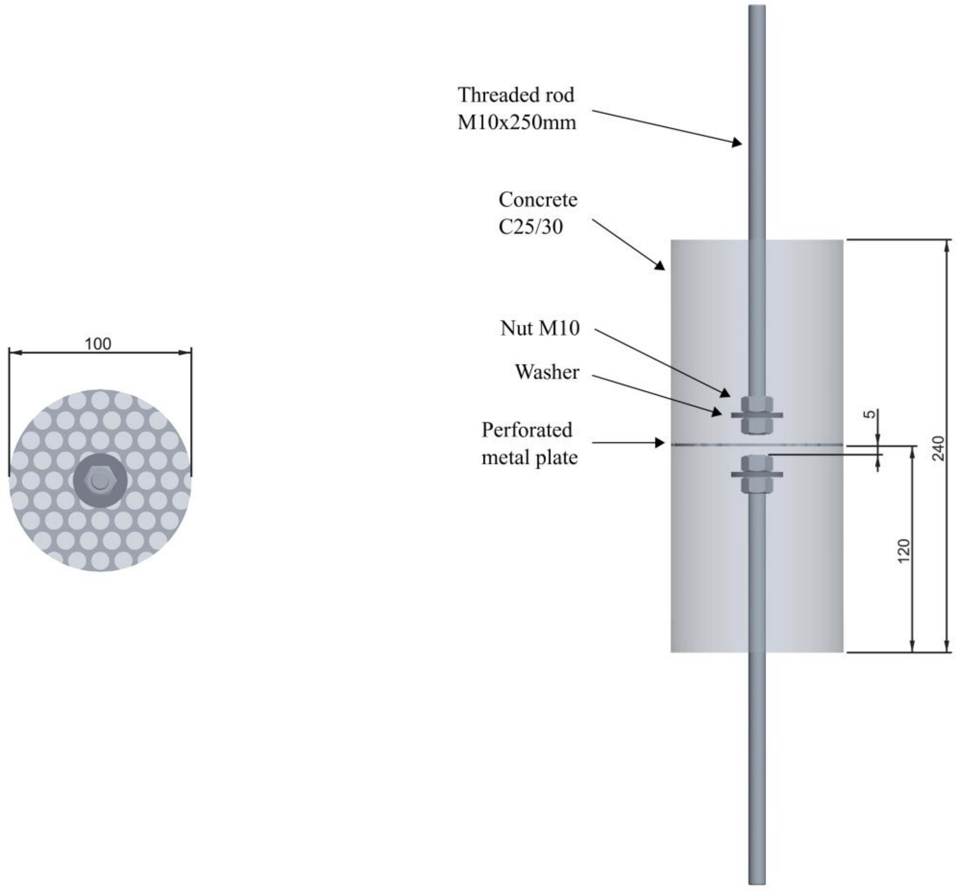
Figure 6.7: Fracture surfaces of the tested specimen of series 2.1 and 2.2.

Table 6.3: Results of tension test series 1.1 and 1.2.

Series	Type	$F_{T,peak}$ [kN]	$\sigma_{T,peak}$ [MPa]	Curing time [days]
2.1	R10T12.7	7.206	0.917	11
2.1	R12T15.55	-	-	11
2.2	R10T12.7	9.031	1.150	7
2.2	R12T15.55	9.755	1.242	7

6.1.2 Series 2.1

A second series (series 2.1) was produced to check the fracture behaviour without a welded connection between the perforated metal plates and the threaded rods. The specimen dimensions and the used material equal the first series. The distance between the threaded rod and the perforated metal plate in the upper half was decreased to 5 mm. The changed geometry of the specimen of series 2.1 is shown in Figure 6.8.

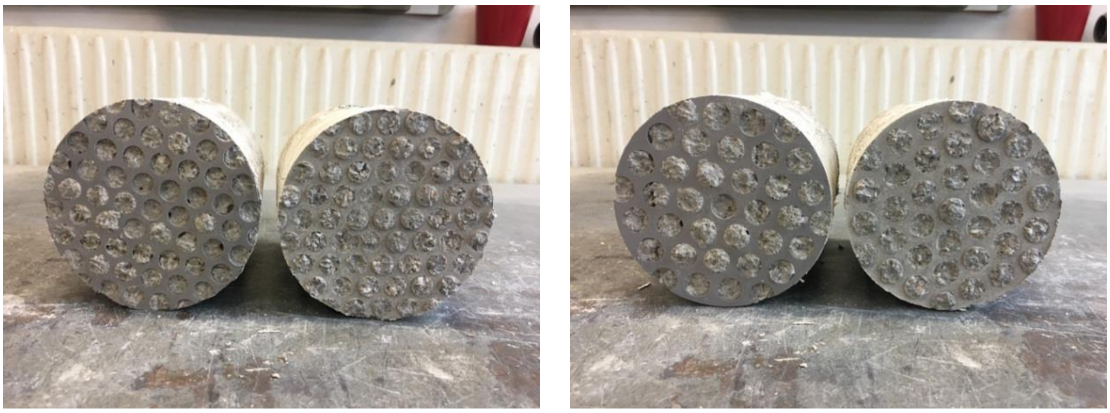


(a) Top view of the specimen.

(b) Front view of the specimen.

Figure 6.8: Geometry of the specimen of series 2.1.

Figure 6.9 shows the specimen after the performed tension test. The tensile strength ($\sigma_{T,peak}$) reached a value of 1.59 MPa with a hole diameter of 10 mm. The specimen with a hole diameter of 12 mm yielded an approximately 24 % lower tensile strength ($\sigma_{T,peak}$) of 1.29 MPa (see Table 6.4).



(a) R10T12.7.

(b) R12T15.55.

Figure 6.9: Fracture surfaces of the tested specimen of series 2.1.

Table 6.4: Results of tension test series 2.1.

Series	Type	$F_{T,peak}$ [kN]	$\sigma_{T,peak}$ [MPa]	Curing time [days]
3.1	R10T12.7	12.510	1.593	11
3.1	R12T15.55	10.099	1.286	11

6.1.1 Comparison of the results of the individual test series

As already mentioned the tension tests were performed to investigate the removability of the concrete from the perforated metal plate. Thereby, the first and second series yielded good results. If one compares the stress-strain behaviour of the test series 1.1, 1.2 and 2.1 (Figure 6.10) it can be observed that there is no significant influence regarding the used hole diameters (10 and 12 mm). The behaviour of all specimen is very similar. The tensile strength ($\sigma_{T,peak}$) ranges from 0.92 MPa to 1.59 MPa for a hole diameter of 10 mm and from 1.24 MPa to 1.29 MPa for a hole diameter of 12 mm. It can be seen that the specimen of series 1 absorb less tensile stress than the specimen of series 2. This is due the fact that the threaded rods in series 2 are not directly connected to the perforated metal plate and thus more strain (ε) is allowed before the specimen fails. For the specimen of series 1, the tensile force (F_T) is transferred directly to the perforated metal plate located in the intended fracture plane, causing the specimen to fail prematurely. With respect to costs and usability in on-site operation a hole diameter of 12 mm is found to be appropriate.

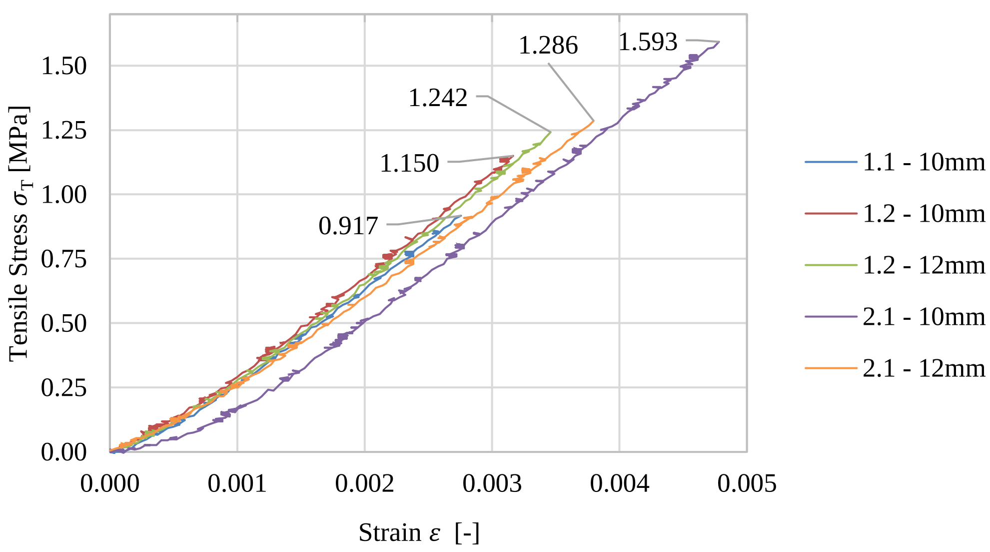


Figure 6.10: Tensile stress-strain graph of series 1.1, 1.2 and 2.1.

6.1.2 Comparison with expanded metal

Expanded metal has a less dense contact area combined with a lower stiffness compared to the perforated metal plates. The results of the tension tests of version “Wenger” with perforated metal plate cannot be compared directly with the results of version “Staudacher” (Staudacher, 2016) with expanded metal. A purely qualitative evaluation of the specimen with expanded metal was carried out without declaration of the tensile strength ($\sigma_{T,peak}$).

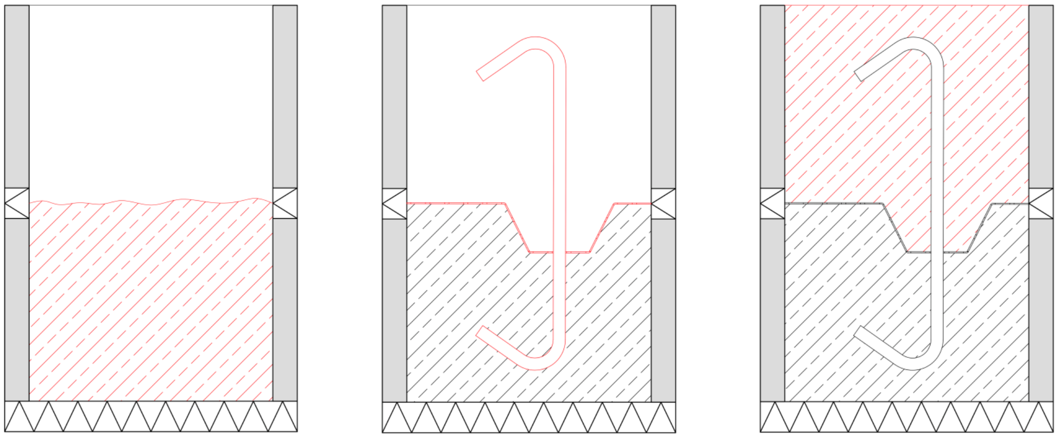
6.2 Shear tests

Shear tests were performed to investigate the maximum transferable shear force of the redesigned CE and the fleece layer in case of a temporary top heading invert. All tests were performed under constant normal load (CNL) condition. Following test series with two tests each were performed:

- **Series S1:** Application of the CE only to investigate the shear resistance due to friction and the geometry of the shear cleat. This state simulates the situation before excavation of the bench.
- **Series S2:** Geometry and material according to the on-site setup to investigate the shear resistance of the CE and the incorporated connection reinforcement. This setup simulates the situation after the excavation of the bench.
- **Series S3:** Fleece is incorporated in the test specimen as a separating layer. It is intended to facilitate the demolition of a temporary top heading invert. Here, the situation with existing shotcrete lining of the temporary top heading invert is simulated.
- **Series S4:** The composition of the specimen is similar to series S3. In order to simulate the rough and irregular surface of the shotcrete, a fine gravel with a grain size of 2-4 mm is additionally sprinkled on the separating layer.

6.2.1 Specimen preparation

All specimens were produced in two layers using concrete of strength class C25/30. First, the lower shear box was filled with concrete and the CE or fleece was subsequently inserted into the fresh concrete at the level of the shear joint. In order to simulate the on-site installation conditions, the lower half of the specimen cured for one day before the upper half was concreted. All specimen of each series cured for 9 (lower half) or 8 days (upper half), respectively. The necessary production stages are shown in Figure 6.11 and Figure 6.12.



(a) Lower shear box filled with concrete.

(b) Placement of the CE on the concrete.

(c) Upper shear box filled with concrete.

Figure 6.11: Schematic representation of the production stages for series S2.

(a) CE with fixed connection reinforcement.

(b) Placement of the CE on the concrete.

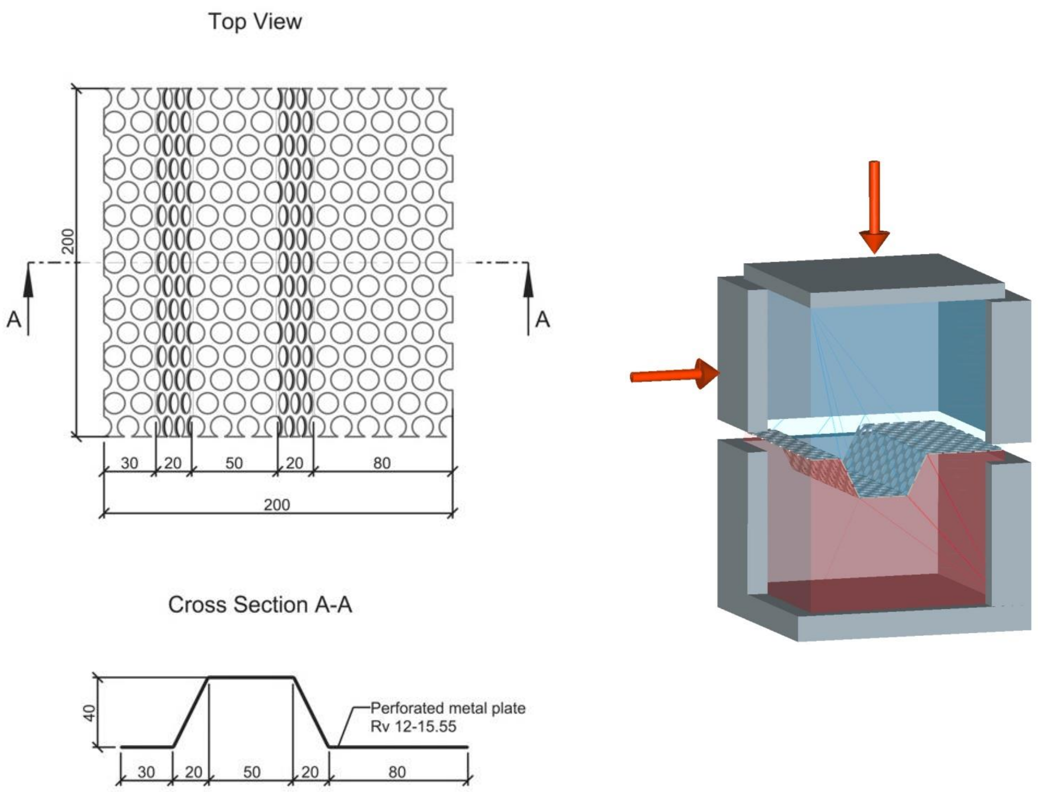
(c) Concreting of the upper shear box.

Figure 6.12: Production of the test specimens shown on the basis of series S2.

The geometry and the materials used for the different test series are shown below:

Series S1

The tested CE is a perforated metal plate of type R12T15.55 with a thickness of 1.0 mm. The data of the used plate is given in Table 6.1. The dimensions as well as the geometry had to be modified for the conduction of the shear test. Hence, the dimensions of the shear cleat were maintained. The dimensions of the element were reduced from 50 mm to 30 mm on the cavity-side and from 100 mm to 80 mm on the side of the rock mass. The vertical lug on the cavity-side of the CE had been omitted. The geometry of the perforated metal plate as well as a 3D illustration is shown in Figure 6.13. Compared to the real installation variant of the CE on-site, the element in the specimen was installed inverted. This was carried out for production-related reasons to be able to backfill the entire CE, especially the shear cleat, with concrete.

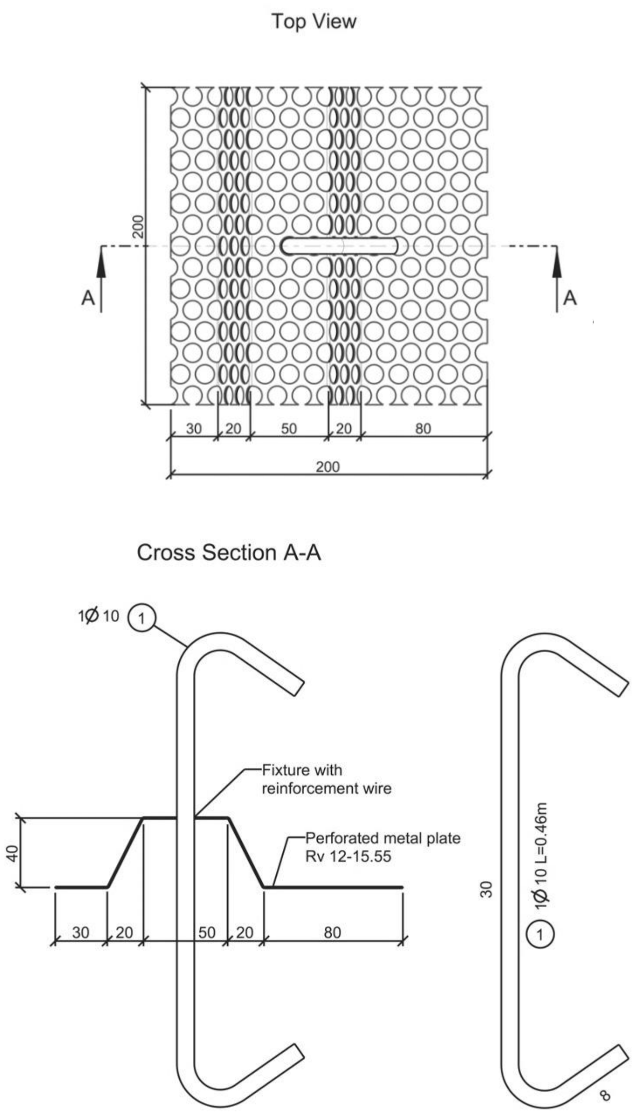


(a) Geometry of the CE. (b) 3D illustration of the shear test.

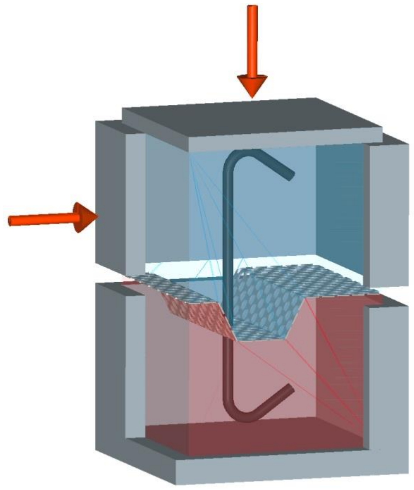
Figure 6.13: Shear test – Series S1.

Series S2

The geometry of the CE used was identical to the one used in test series S1. In addition, one reinforcement bar of type BSt 550 with a nominal diameter of 10 mm was used. In order to maintain the minimum bond length, the reinforcement bar was executed with two end hooks. The test setup was similar to the setup used in reality (but as in series 1 installed inverted). The geometry of the CE and the reinforcement bar, as well as a 3D illustration of the test is shown in Figure 6.14.



(a) Geometry of the CE and the reinforcement bar.



(b) 3D illustration of the shear test.

Figure 6.14: Shear test – Series S2.

Series S3 and S4

In test series S3 and S4, the fleece of type Drefon RVS 3850-1 was tested. During tunnel construction the fleece serves as separating layer for an easier demolition of the shotcrete lining of the temporary top heading invert (details see chapter 5). For the shear tests the fleece was located in the predefined shear plane. In order to simulate the uneven or rough surface of the shotcrete, a fine gravel with a grain size of 2-4 mm was dusted onto the surface of the concrete in test series 4. The main characteristics of the fleece are listed in Table 6.5 (Manifattura Fontana, 2014). A complete datasheet with the essential characteristics can be found in Appendix C. The test setup is shown in Figure 6.15, the surface of the shear joint of series S4 in Figure 6.16.

Table 6.5: Fleece Drefon RVS 3850-1 – Main characteristics (Manifattura Fontana, 2014).

Main characteristics	Mean value	Unit
Tensile strength MD (manufacturing direction)	25.40	kN/m
Tensile strength CMD (crosswise manufacturing direction)	25.40	kN/m
Elongation MD (manufacturing direction)	75.00	%
Elongation CMD (crosswise manufacturing direction)	75.00	%
Static puncture resistance	4,100.00	N
Water permeability v_i 50 mm	68.00	$l/(s\ m^2)$
Water permeability at 20 kPa, i = 1	6.50	$10^{-6}\ m^2/s$

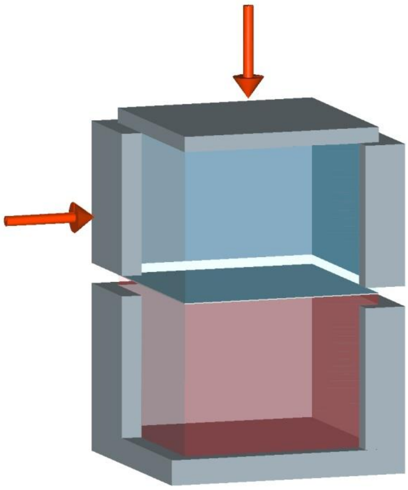


Figure 6.15: 3D illustration of the shear test – Series S3 and S4.

Figure 6.16: Surface of the shear joint of series S4.

6.2.2 Test configuration and test procedure

A MTS direct shear test apparatus with shear box dimensions of 200 x 200 x 150 mm (length x width x height) as shown in Figure 6.17 was used. A 2 cm thick insulation board was inserted between the upper and lower shear box during specimen preparation.

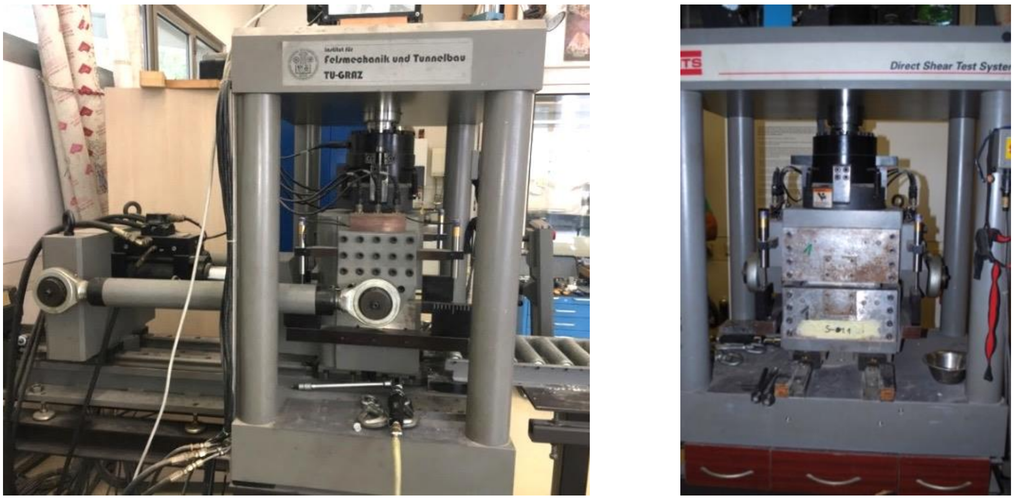


Figure 6.17: Shear testing device for the direct shear tests.

Figure 6.18 shows a schematic sketch of the shear testing device used to carry out the shear tests.

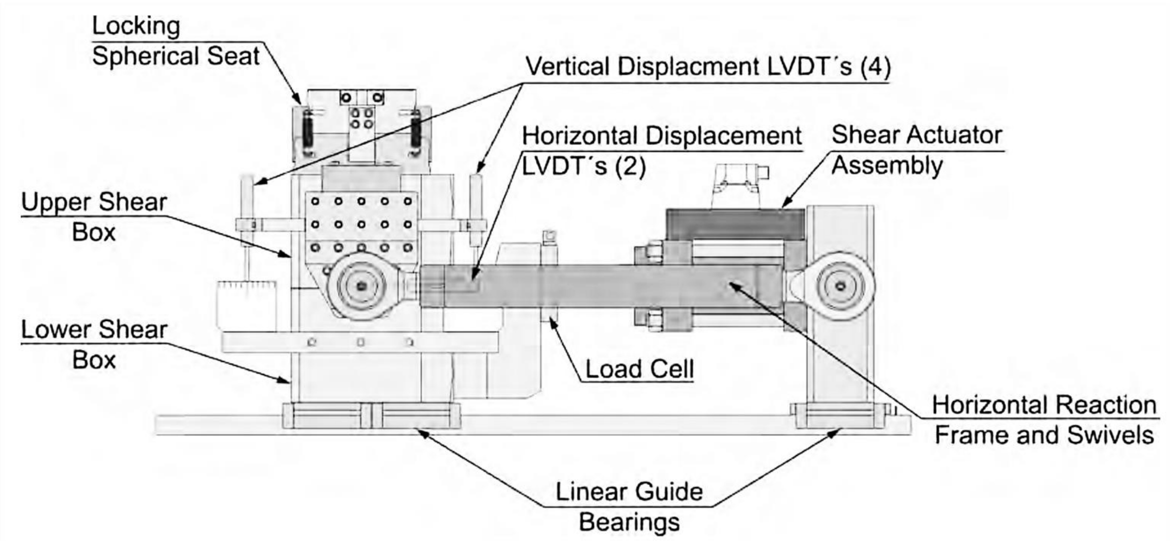


Figure 6.18: Shear testing device including designations (Pilgerstorfer, 2014).

After positioning of the test specimen in the shear testing device, the normal force (F_N) was applied under CNL conditions. The specimen was subsequently sheared off horizontally with a constant feed speed (v) until a predefined horizontal displacement ($w_{h,max}$) has been reached. The values of Staudacher (2016) served as a guideline. Table 6.6 shows the applied normal force (F_N) and the respective feed speed (v) with the maximum displacement ($w_{h,max}$). Figure 6.19 shows the test configuration for series S2.

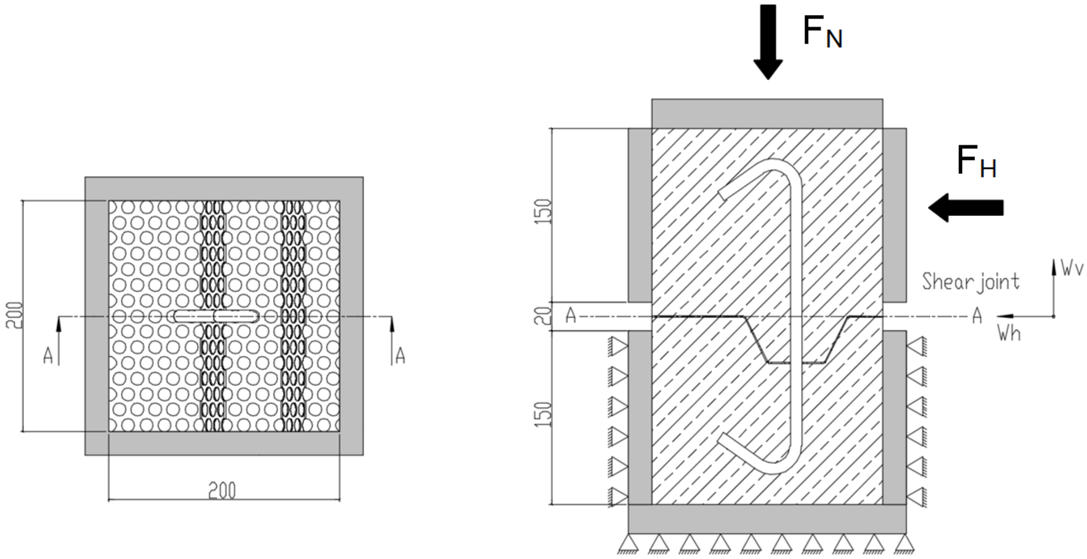


Figure 6.19: Test configuration of the shear test for series S2.

Table 6.6: Test configuration of the individual test specimens.

Designation	Designation of the specimen	F_N [kN]	v [mm/min]	$w_{h,max}$ [mm]
Series S1	S1.1	50	0.5	10
	S1.2	80	0.5	10
Series S2	S2.1	50	0.5	23
	S2.2	80	0.5	23
Series S3	S3.1	50	0.5	17
	S3.2	80	0.5	17
Series S4	S4.1	50	0.5	19
	S4.2	80	0.5	19

Following values were recorded at each test procedure:

- Time t_{ST} [s]
- Horizontal force F_H [kN]
- Horizontal displacement w_h [mm]
- Vertical displacement w_v [mm]

6.2.3 Results and discussion

The shear resistance was determined from the performed shear tests. Therefore, the main interest of the evaluation was on the determined horizontal force (F_H). Thereby, the forces are converted into stresses using the shear area of 40,000 mm^2 (200 x 200 mm). Evaluation of the test data is performed for each series and the failure mechanism is examined in detail. A comparison of the individual samples is carried out for series S1 and S2 (connecting element) as well as S3 and S4 (fleece), respectively.

6.2.3.1 Connecting element – Series S1 and S2

Series S1

Table 6.7 shows the results of the specimens of series S1 without additional connection reinforcement. The measured shear strength (τ_{peak}) yields 3.44 N/mm2 for specimen S1.1 and 4.00 N/mm^2 for specimen S1.2. The representative fracture pattern is illustrated in Figure 6.20. The maximum shear stress (τ_{peak}) occurs at a shear displacement ($w_{h,Fpeak}$) of 0.81 ÷ 0.82 mm which equals a maximum shear strain ($\varepsilon_{h,Fpeak}$) of 0.41 %. Since no additional reinforcement is used in this test series, brittle fracture occurs. The failure occurs directly in the area of the perforated metal plate because here the bond is the lowest. After the fracture, the residual shear resistance (τ_{res}) is only influenced by the friction between perforated metal plate and concrete.

Table 6.7: Results of the shear test of series S1.

Specimen	F_N [kN]	$\sigma_{N,peak}$ N/mm^2]	$F_{H,peak}$ [kN]	τ_{peak} [N/mm^2]	$w_{h,Fpeak}$ [mm]	$F_{H,res}$ [kN]	τ_{res} [N/mm^2]
S1.1	50	1.25	138	3.44	0.81	44	1.10
S1.2	80	2.00	160	4.00	0.82	71	1.78

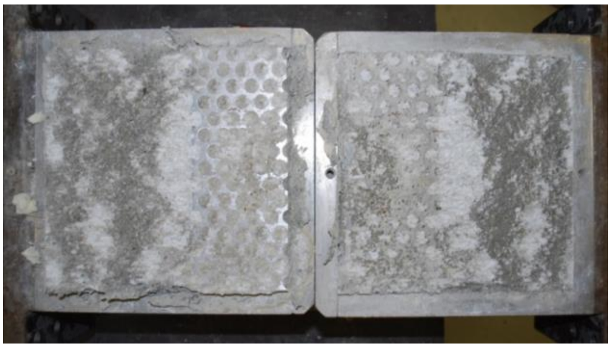


Figure 6.20: Representative fracture pattern of series S1.

Series S2

The results of series S2 with additional reinforcement can be taken from Table 6.8. The measured shear strength (τ_{peak}) yields 3.88 N/mm^2 for specimen S2.1 and 4.29 N/mm^2 for specimen S2.2. The maximum transmittable shear stress (τ_{peak}) is reached between a shear displacement ($w_{h,Fpeak}$) of 0.90 ÷ 0.92 mm and equals a shear strain ($\varepsilon_{h,Fpeak}$) of 0.45 ÷ 0.46 %. The representative fracture pattern is visualized in Figure 6.21. Equal to series S1 the fracture occurs in the region of the perforated metal plate because here the bond is the lowest. A closer examination of the test results reveals that the incorporated reinforcement bar increases the transferable shear force by about 7 to 12 %. The deformed reinforcement can be seen in Figure 6.21 (c).

Table 6.8: Results of the shear test of series S2.

Specimen	F_N [kN]	$\sigma_{N,peak}$ [N/mm²]	$F_{H,peak}$ [kN]	τ_{peak} [N/mm²]	$w_{h,Fpeak}$ [mm]	$F_{H,res}$ [kN]	τ_{res} [N/mm²]
S2.1	50	1.25	155	3.88	0.90	85	2.13
S2.2	80	2.00	171	4.29	0.92	95	2.38

(a) Representative fracture pattern after the shearing process.

(b) Exposed reinforcement in the upper half of the specimen for a better visibility of the deformations.

(c) Exposed reinforcement in both halves of the specimen for a better visibility of the deformations.

Figure 6.21: Representative fracture pattern and deformations of the reinforcement of series S2.

Comparison of series S1 and S2

Figure 6.22 (shear stress-strain graph) and Figure 6.23 (vertical vs. horizontal displacement graph) show a comparison of the test data of series S1 and S2. The specimens with a reinforcement bar (series S2) are illustrated with blue lines, those without reinforcement (series S1) with red lines. All specimens show a relatively similar behaviour, but series S2 yields a higher shear strength (τ_{peak}) than series S1 due to the incorporated reinforcement. As the normal stress (σ_N) increases, both the maximum shear stress (τ_{peak}) and the residual shear stress (τ_{res}) increase due to an increase of the friction component.

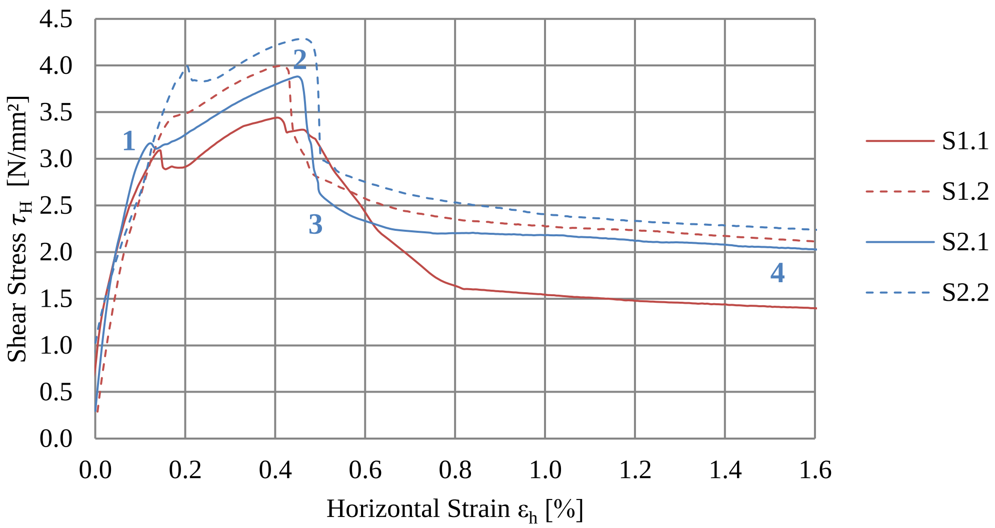


Figure 6.22: Shear stress vs. horizontal strain graph, comparison of series S1 and S2.

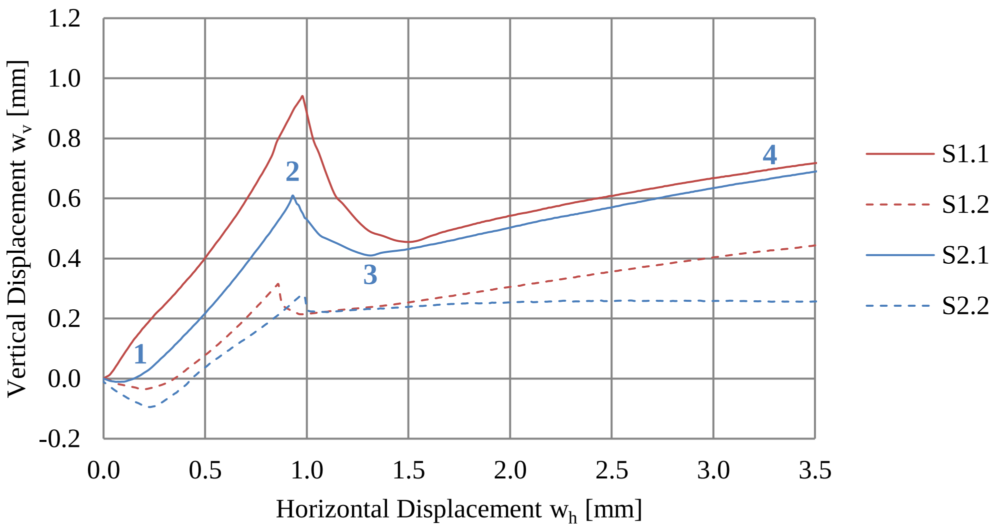


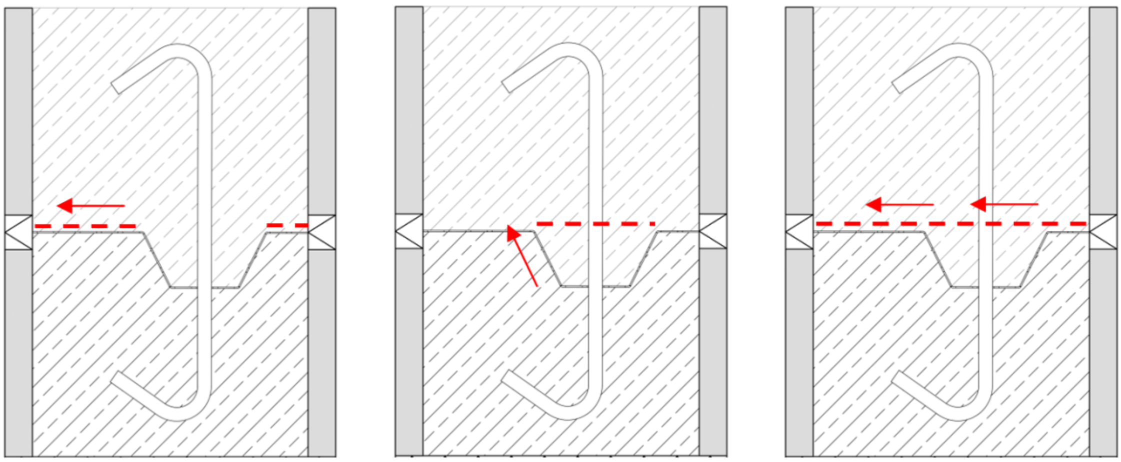
Figure 6.23: Vertical displacement vs. horizontal displacement graph, comparison of series S1 and S2.

Based on the shear stress (τ_H) vs. horizontal strain (ε_h) graph (Figure 6.22) and the vertical displacement (w_v) vs. horizontal displacement (w_h) graph (Figure 6.23) of test series S2.1 and four distinctive points in the curve, the failure mechanism is explained as representative of all test series.

- **Point 1:** The applied horizontal force (F_H) increases steadily until the failure of the bond between the perforated metal plate and concrete occurs, visualized in Figure 6.24 (a).
- **Point 2:** After reaching point 1, a dilation along the trapezoidal shear cleat can be observed (Figure 6.24 (b)). The horizontal force (F_H) continues to increase as the shear cleat provides additional resistance in addition to the friction between perforated metal plate and concrete. Furthermore, the impact of the reinforcement on the shear resistance (τ_H) increases with increasing shear displacement (w_h) (only for series S2). At point 2, the concrete fails in the

area of the shear cleat and a significant drop in the shear resistance (τ_H) can be noticed.

- **Point 3:** Point 3 indicates that the residual shear resistance (τ_{res}) is reached along the predefined shear joint, seen in Figure 6.24 (c). In series S1, the shear forces (F_H) are transmitted purely by the friction between metal and concrete. The increased shear resistance (τ_{peak}) of series S2 is related to the incorporated reinforcement bar.
- **Point 4:** This point inidcates that the reinforcement bar does not contribute anymore to the shear resistance (τ_H) as a uniform shear stress is observed.



(a) Point 1: Failure of the bond between concrete and perforated metal plate occurs.

(b) Point 2: Dilation along the shear cleat with subsequent failure of the concrete in this area.

(c) Point 3 and 4: Uniform shearing along the shear joint occurs.

Figure 6.24: Failure mechanism of series S1 and S2.

The results show that the specimens with incorporated reinforcement yield a higher shear resistance (τ_{peak}). The maximum shear resistance per meter results in roughly 850 kN for a 20 cm thick shotcrete liner.

Table 6.9 shows the influence of the reinforcement bar onto the shear resistance. One can see that the shear strength (τ_{peak}) increases by 10 %. Most noticeable is the effect onto the residual shear strength (τ_{res}) with an increase of 65 %. The shear forces (F_H) are thus transferred both by friction between metal and concrete as well as the contribution of the reinforcement steel. In reality, the reinforcement steel would thus be increasingly deformed until it is sheared off.

Table 6.9: Contribution of the reinforcement bar onto shear strength/resistance.

Parameter	Unit	S1			S2			Influence
		S1.1	S1.2	Av.	S2.1	S2.2	Av.	of Steel
τ_{peak}	N/mm^2	3.44	4.00	3.72	3.88	4.29	4.08	+ 10 %
τ_{res}	N/mm^2	1.10	1.78	1.44	2.13	2.38	2.25	+ 65 %
$F_{H,peak}$	kN	137.66	159.83	148.74	155.27	171.45	163.36	+ 15 %
$w_{h,Fpeak}$	mm	0.81	0.82	0.82	0.90	0.92	0.91	+ 12 %

In addition, to determine the exact contribution of the reinforcement to the shear strength (τ_{peak}) additional tests can be performed to get knowledge about the failure and yield limits of the steel rod. Parameters like the axial strain and the axial force of the steel rod have to be measured. Similar tests have already been carried out by Pellet and Egger (1996). There, the behaviour of bolted rock joints subjected to shearing was examined. Pellet and Egger came to the conclusion that the contribution of the bolt to the residual shear strength (τ_{res}) in the joint after the failure occurred can be divided into a cohesive component which is acting parallel to the joint and into a limiting term due to the normal force which is applied to the specimen (Pellet & Egger, 1996). This statement also applies to the shear tests of series S2 with perforated metal plate and additional reinforcement steel. Another factor influencing the shear behaviour is, among other things, the strength of the concrete used.

Comparison of perforated metal plates and expanded metal

If one compares the test results of the specimens of Staudacher (2016) with expanded metal, similar characteristics to the specimen with the perforated metal plate can be observed. The results for expanded metal of the version “Staudacher” (series S and S-B) (Staudacher, 2016) are indicated with red lines, the results of perforated metal plate of version “Wenger” (series S1 and S2) are indicated with blue lines. Figure 6.25 illustrates the shear stress (τ_H) vs. horizontal strain (ε_h) behaviour for a CE without connection reinforcement, Figure 6.26 for a CE with connection reinforcement. The curves of the two different versions show a similar behaviour in the initial area for both specimen types. With respect to the failure mechanisms described above, the applied horizontal force (F_H) increases steadily until the failure of the bond between the perforated metal plate and concrete occurs. A significant drop in the shear stress (τ_H) can be noticed after reaching the shear strength (τ_{peak}) at point 2 after the concrete fails in the area of the shear cleat for the samples with perforated metal plates. For the specimen with expanded metal, the shear stress (τ_H) decreases more slowly, recognizable by the flatter course of the curve. This behaviour can be attributed to the softer material and the rough surface of the expanded metal. Afterwards (point 3) the residual shear strength (τ_{res}) is reached along the predefined shear joint, with almost similar values for both the expanded metal and the perforated metal plate. In series S (version “Staudacher”) and S1 (version “Wenger), the shear forces are transmitted purely by the friction between metal and concrete. The additional shear resistance (τ_H) of series S-B (version “Staudacher”) and S2 (version “Wenger) is related to the incorporated reinforcement bar.

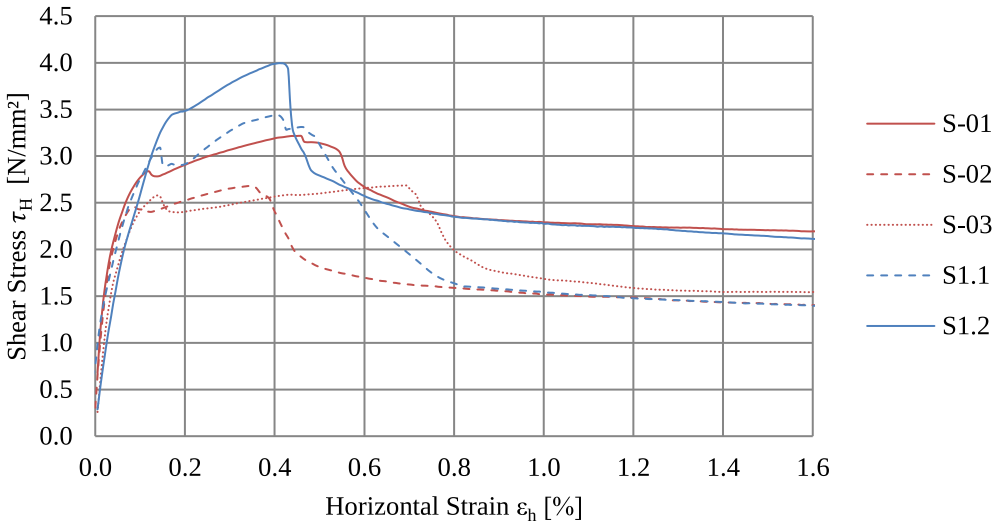


Figure 6.25: Shear stress vs. horizontal strain graph, comparison of series S1 (Wenger) and S (Staudacher, 2016) for connecting element without connection reinforcement.

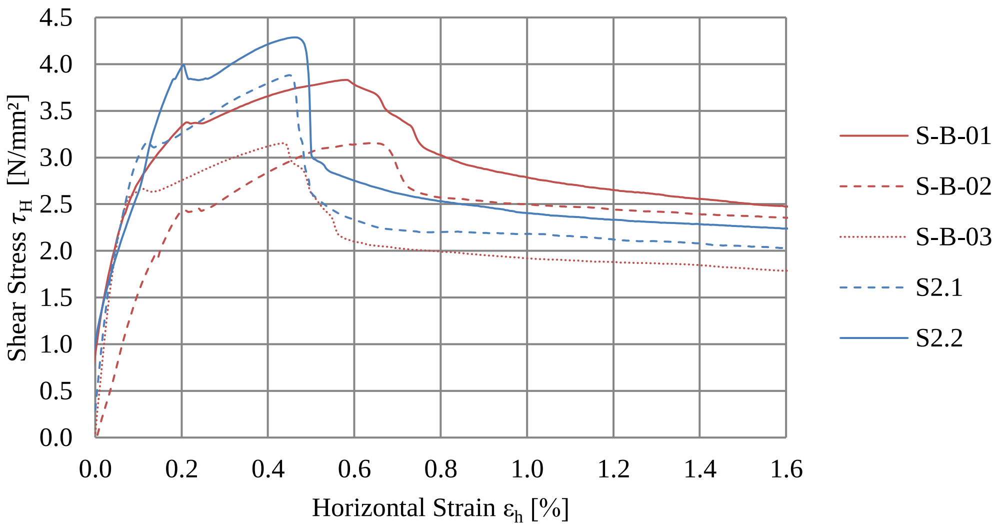


Figure 6.26: Shear stress vs. horizontal strain graph, comparison of series S2 (Wenger) and S-B (Staudacher, 2016) for connecting element with connection reinforcement.

The comparison shows that using a perforated metal plate results in a higher shear resistance (τ_{peak}) of the CE with and without reinforcement. The shear resistance for the specimens without reinforcement is approximately 24 ÷ 28 % higher, for the specimens with reinforcement between 12 ÷ 23 %. The higher shear resistance (τ_{peak}) is most likely due to the better bond of the concrete of the upper and lower shear box. Due to the geometry and the hole pattern of the perforated metal plate, around 55% of the upper and lower halves of the specimen is bonded by concrete in the area of the separating surface. Another influence on the test results derive from the modified geometry of the shear cleat and the higher strength of the used concrete. Table 6.10 shows the detailed values of the compared results.

Table 6.10: Comparison of version “Wenger” and “Staudacher” (2016) – Connecting element without and with connection reinforcement.

		Without Reinforcement			With Reinforcement		
$F_{N,peak}$ [kN]		Wenger S1.1	Staudacher S-02	Diff.	Wenger S2.1	Staudacher S-B-02	Diff.
50	$\sigma_{N,peak}$ [N/mm^2]	1.25	1.25	0.00	1.25	1.25	0.00
	$F_{H,peak}$ [kN]	138.00	107.00	+31.00	155.00	126.00	+29.00
	τ_{peak} [N/mm^2]	3.44	2.68	+0.76	3.88	3.15	+0.73
	$w_{h,Fpeak}$ [mm]	0.81	0.69	+0.12	0.90	1.29	-0.39
	$F_{H,res}$ [kN]	44.00	49.00	-5.00	85.00	87.00	-2.00
	τ_{res} [N/mm^2]	1.10	1.22	-0.12	2.13	2.17	-0.04
		Wenger S1.2	Staudacher S-01	Diff.	Wenger S2.2	Staudacher S-B-01	Diff.
80	$\sigma_{N,peak}$ [N/mm^2]	2.00	2.00	0.00	2.00	2.00	0.00
	$F_{H,peak}$ [kN]	160.00	129.00	+31.00	171.00	153.00	+18.00
	τ_{peak} [N/mm^2]	4.00	3.22	+0.78	4.29	3.83	+0.46
	$w_{h,Fpeak}$ [mm]	0.82	0.91	-0.09	0.92	1.16	-0.24
	$F_{H,res}$ [kN]	71.00	71.00	0.00	95.00	95.00	0.00
	τ_{res} [N/mm^2]	1.78	1.78	0.00	2.38	2.39	-0.01

In Figure 6.27 and Figure 6.28 the graphs of the Mohr-Coulomb failure criterion are compared for the specimen without and with additional connection reinforcement. The results of the version “Wenger” with perforated metal plate are indicated with blue lines, the results of the version “Staudacher” (Staudacher, 2016) with expanded metal are indicated with red lines. Since the tests were carried out with just two specimens per series only qualitative results can be presented. To obtain more reliable data, further tests must be performed with a minimum of three specimens per series. It is denoted that the graph for a CE with additional reinforcement (Figure 6.28) is only presented for a comparison with the graph of the version without connection reinforcement (Figure 6.27). Due to the incorporated reinforcement, the Mohr-Coulomb criterion cannot be applied as in the sense intended, because the two halves of the specimen are still connected to each other after the failure occurs and thus falsify the value of the residual shear stress (τ_{res}) The friction angles and the cohesion are listed in Table 6.11 and Table 6.12. As seen in Figure 6.27 the peak friction angle (φ_{peak}) is almost the same for both expanded metal and perforated metal plate. However, the specimen with perforated metal plate of the version “Wenger” yielded an approximately 0.8 N/mm^2 higher shear strength (τ_{peak}) for both tests with a normal force ($F_{N,peak}$) of 50 kN and 80 kN. The peak cohesion (c_{peak}) of the specimen with perforated metal plate is 0.74 N/mm² higher than that for specimen with expanded metal. The residual friction angle (φ_{res}) of version "Wenger" is 5° higher than that of version "Staudacher".

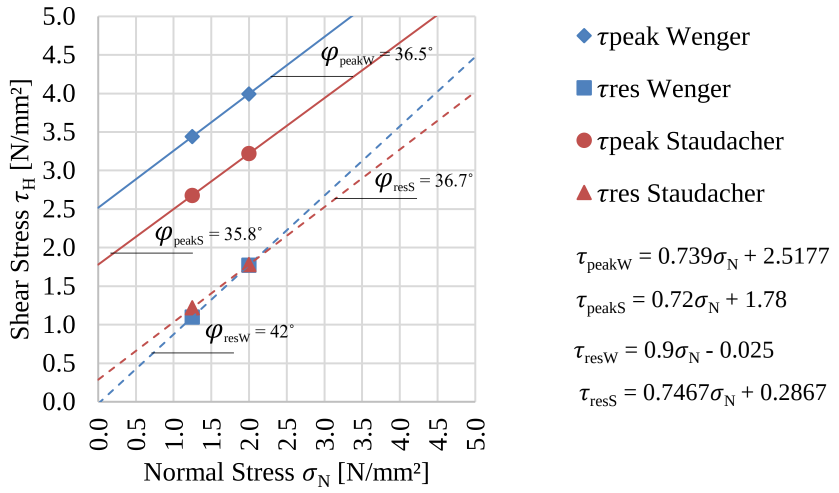


Figure 6.27: Comparison of MC-graph of version "Wenger" (blue) and "Staudacher" (2016) (red) for connecting element without connection reinforcement.

Table 6.11: Comparison of friction angle and cohesion of version "Wenger" (S1) and version "Staudacher" (2016) (S) for connecting element without connection reinforcement.

Version	Series	φ_{peak} [°]	φ_{res} [°]	c_{peak} [N/mm²]	c_{res} [N/mm²]
Wenger	S1	36.50	42.00	2.52	-0.03
Staudacher	S	35.80	36.70	1.78	0.29
Difference		+0.70	+5.30	+0.74	-0.31

As seen in Figure 6.28 the shear strength (τ_{peak}) for specimen with perforated metal plate and additional connection reinforcement of version "Wenger" is higher. However, a 13.9° steeper failure envelope results for the specimen with expanded metal with a value of 42.2°. The peak cohesion (c_{peak}) is 1.19 N/mm² higher for specimen with perforated metal plate. The residual shear strength (τ_{res}) as well as the residual cohesion (c_{res}) and the residual friction angle (φ_{res}) are almost the same for both versions "Wenger" and "Staudacher".

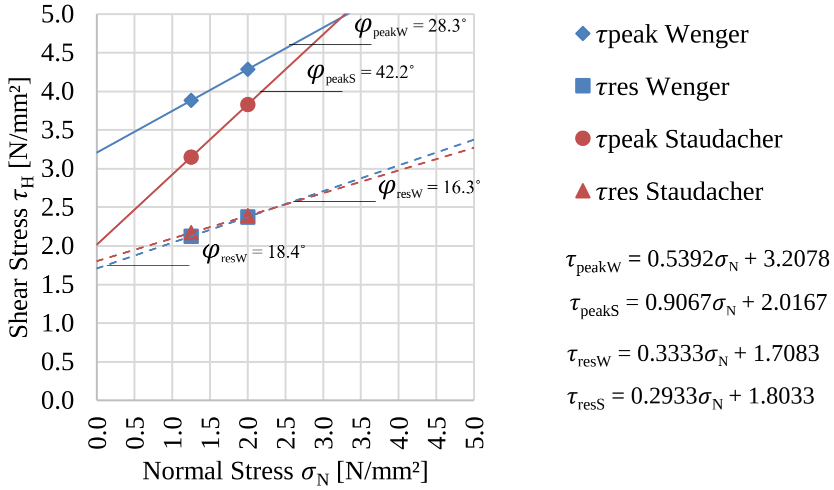


Figure 6.28: Comparison of MC-graph of version “Wenger” (blue) and “Staudacher” (2016) (red) for connecting element with connection reinforcement.

Table 6.12: Comparison of friction angle and cohesion of version “Wenger” (S2) and version “Staudacher” (2016) (S-B) for connecting element with connection reinforcement.

Version	Series	φ_{peak} [◦]	φ_{res} [◦]	c_{peak} [N/mm²]	c_{res} [N/mm²]
Wenger	S2	28.30	18.40	3.21	1.71
Staudacher	S-B	42.20	16.30	2.02	1.80
Difference		-13.90	+2.10	+1.19	-0.10

In Figure 6.29 and Figure 6.30 the graphs of the vertical displacements (w_v) vs. horizontal displacements (w_h) are compared for the specimen without and with additional connection reinforcement. The results of version “Wenger” with perforated metal plate are indicated with blue lines, the results of version “Staudacher” (Staudacher, 2016) are indicated with red lines. The sudden drop after the peak point of the curves for specimen with perforated metal plate is related to the smooth surface of the perforated metal plate. At the beginning of the curves a slight contractive behaviour can be seen, which shortly afterwards proceeds in dilatant behaviour for all tests. The specimen without connection reinforcement with an applied normal force ($F_{N,peak}$) of 50 kN have a higher vertical displacement (w_v) than the specimen with 80 kN for both versions “Wenger” and “Staudacher”, seen in Figure 6.29.

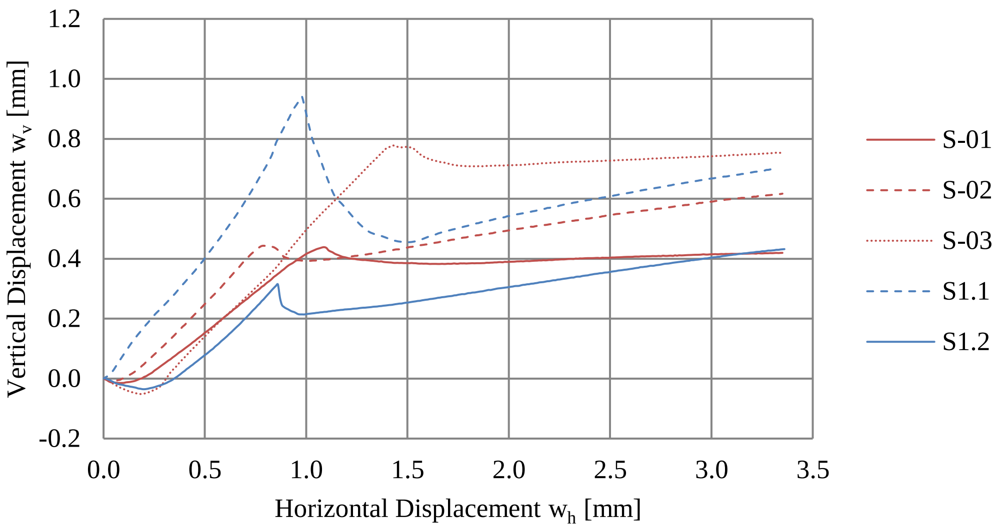


Figure 6.29: Vertical displacement vs. horizontal displacement graph, comparison of series S1 (Wenger) and S (Staudacher, 2016) for connecting element without connection reinforcement.

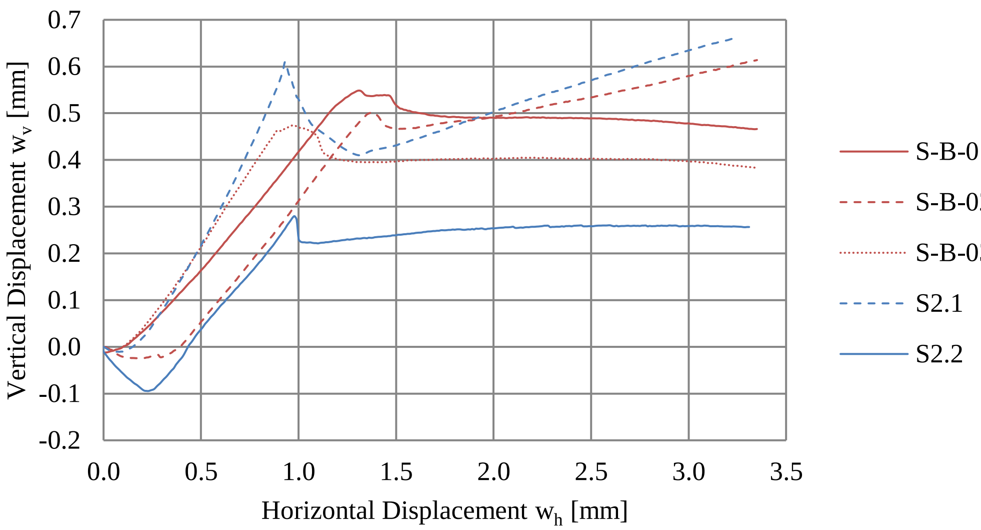


Figure 6.30: Vertical displacement vs. horizontal displacement graph, comparison of series S2 (Wenger) and S-B (Staudacher, 2016) for connecting element with connection reinforcement.

6.2.3.2 Fleece – Series S3 and S4

Series S3

Table 6.13 shows the results of the specimens of series S3 with incorporated fleece of type Drefon RVS 3850-1. The measured shear strength (τ_{peak}) yields 1.51 N/mm^2 for specimen S3.1 and 1.92 N/mm^2 for specimen S3.2. The maximum transferable shear stress occurs at a shear displacement ($w_{h,Fpeak}$) of 3 mm which equals a maximum shear strain ($\varepsilon_{h,Fpeak}$) of 1.5 %. The failure occurs directly in the area of the fleece because here the bond is the lowest. The representative fracture pattern is illustrated in Figure 6.31. If one considers the purpose and the boundary conditions on site, the minor shear resistance of roughly 1.5 N/mm^2 is still sufficient as shear movements in this area are not likely to occur. As already stated the fleece is only intended to serve as an aid for an easier demolition of the shotcrete lining temporary top heading invert.

Table 6.13: Results of the shear test of series S3.

Specimen	$F_{N,peak}$ [kN]	$\sigma_{N,peak}$ [N/mm^2]	$F_{H,peak}$ [kN]	τ_{peak} [N/mm^2]	$w_{h,Fpeak}$ [mm]	$F_{H,res}$ [kN]	τ_{res} [N/mm^2]
S3.1	50	1.25	61	1.51	3.05	23	0.58
S3.2	80	2.00	77	1.92	3.06	38	0.95

Figure 6.31: Representative fracture pattern of the series S3.

Series S4

The results of series S4 with incorporated fleece of type Drefon RVS 3850-1 and additional fine gravel can be taken from Table 6.14. The measured shear strength (τ_{peak}) yields 0.84 N/mm^2 for specimen S4.1 and 1.21 N/mm^2 for specimen S4.2. The maximum transferable shear stress is reached at shear displacement ($w_{h,Fpeak}$) of 0.90 mm and equals a shear strain ($\varepsilon_{h,Fpeak}$) of 0.45 %. The representative fracture pattern is shown in Figure 6.32. Equal to series S3 the fracture occurs in the region of the fleece because here the bond is the lowest.

Table 6.14: Results of the shear test of series S4.

Specimen	$F_{N,peak}$ [kN]	$\sigma_{N,peak}$ N/mm^2]	$F_{H,peak}$ [kN]	τ_{peak} [N/mm^2]	$w_{h,Fpeak}$ [mm]	$F_{H,res}$ [kN]	τ_{res} [N/mm^2]
S4.1	50	1.25	34	0.84	4.14	30	0.75
S4.2	80	2.00	48	1.21	5.33	46	1.15

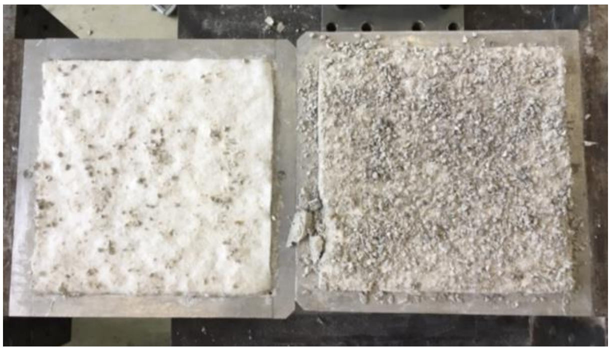


Figure 6.32: Representative fracture pattern with additional fine gravel on the fleece.

Comparison of Series S3 and S4

Figure 6.33 (Shear stress vs. horizontal strain graph) and Figure 6.34 (Vertical displacement vs. horizontal displacement graph) show the comparison of the test results of series S3 and S4. The test specimens with fine gravel on the separating layer (series S4) are indicated with blue lines, those without fine gravel (series S3) with red lines. The comparison of the graph reveals that the additional fine gravel in series 4 reduces the shear strength (τ_{peak}) by about 37 to 45 %. This is due to the reduced bond between concrete and fleece because of the fine gravel. For series S3 the applied horizontal force increases steadily until the maximum shear resistance (τ_{peak}) (point 1) is reached. At this stage, the bond between fleece and concrete fails. From point 1 the test specimen shears off consistently along the predefined shear joint. When reaching point 2 the residual shear capacity is only influenced by the residual friction between concrete and fleece. It is denoted that for series S4 the specimen gathered a continuous increase of the horizontal force (F_H) till the failure occurred and the residual shear strength (τ_{res}) is reached. At the beginning a contractive behaviour can be observed, which shortly afterwards proceeds in dilatant behaviour for series 3 (Figure 6.34). The specimen of series 4 have a contractive behaviour as the additional fine gravel on the separating layer continues to compress.

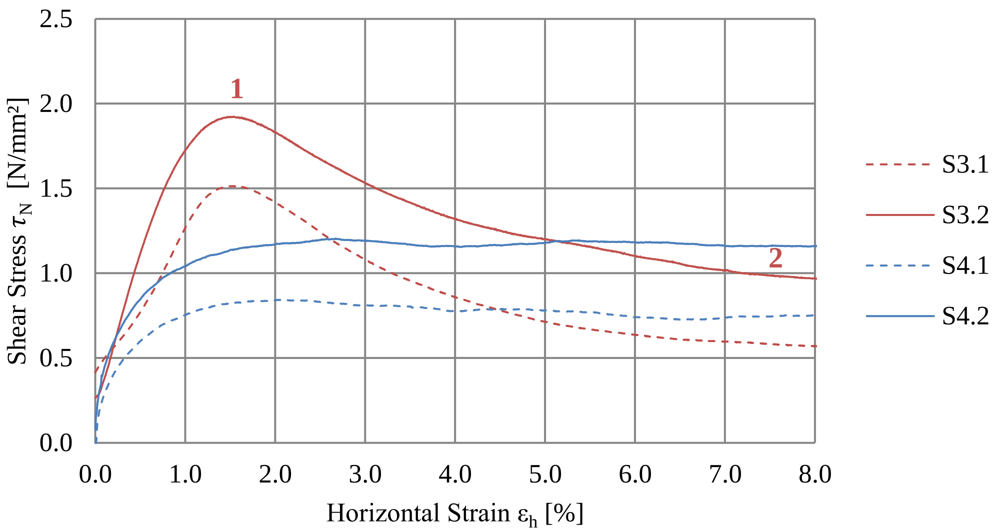


Figure 6.33: Shear stress vs. horizontal strain graph, comparison of series S3 and S4.

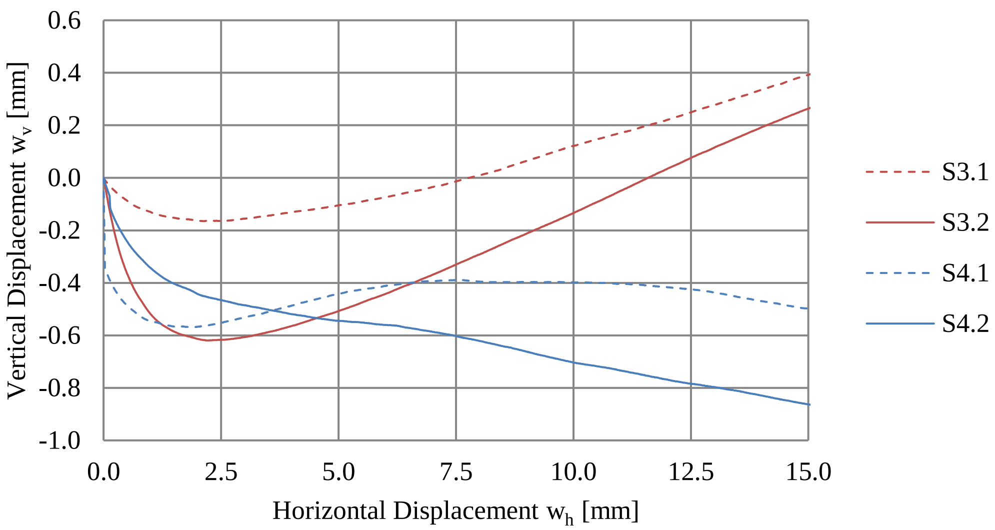


Figure 6.34: Vertical displacement vs. horizontal displacement graph, comparison of series S3 and S4.

Figure 6.35 and Figure 6.36 show the Mohr-Coulomb failure criterion of series 3 and 4. The friction angles and the cohesion are listed in Table 6.15. The peak values are illustrated in blue, the residual values in red. Since the tests were carried out with just two specimens per series only qualitative results can be presented. For series 3 the peak friction angle (φ_{peak}) of 28.6° is 2° higher than the residual friction angle (φ_{res}) of 26.6°. The cohesion (c_{peak}) is 0.83 N/mm^2. In Figure 6.36 it can be seen that the failure in series 4 occurred earlier due to the fine gravel than in series 3. The friction angle continues to increase after the failure and rises from 25.7° at failure (φ_{peak}) to the residual friction angle (φ_{res}) of 28.1°. This behaviour is also due to the low bond of the concrete and the fleece because of the fine gravel. Based on the test results, it can be stated that series 4 does not correspond to reality.

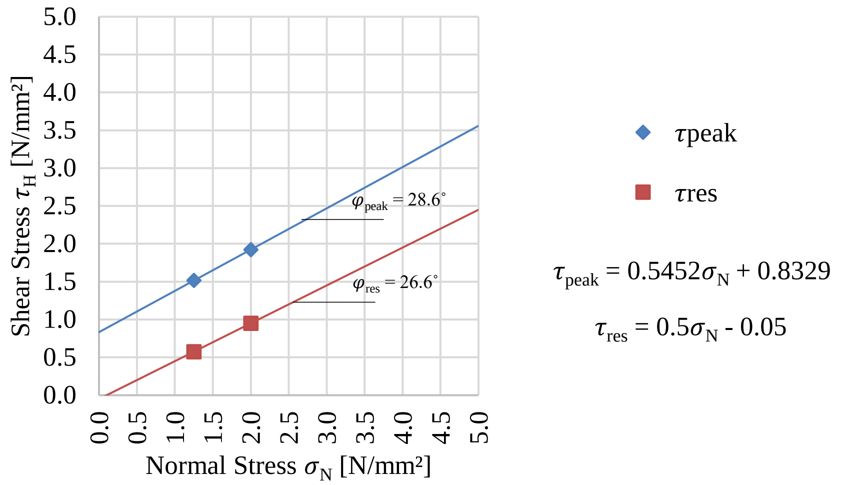


Figure 6.35: MC-graph of series S3.

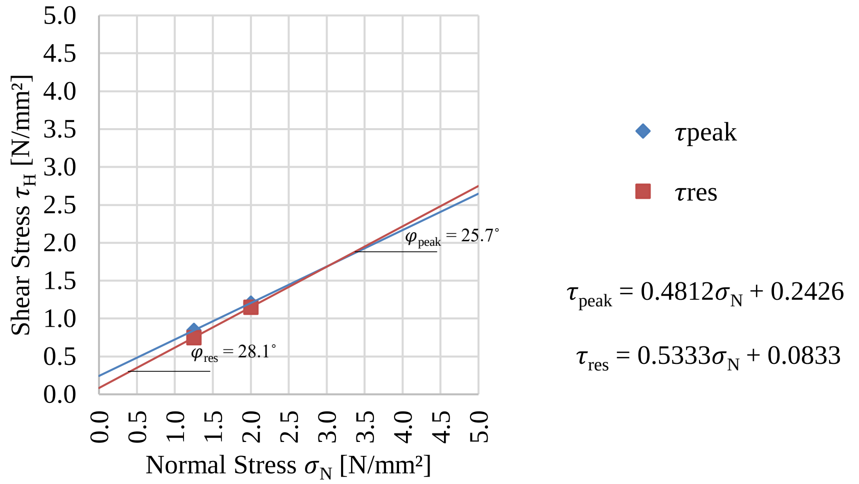


Figure 6.36: MC-graph of series S4.

Table 6.15: Friction angle and cohesion of series S3 and S4.

Series	φ_{peak} [∘]	φ_{res} [∘]	c_{peak} [N/mm^2]	c_{res} [N/mm^2]
S3	28.6	26.6	0.83	0.05
S4	25.7	28.1	0.24	0.08

7 On-site tests

In order to investigate the suitability of the redesigned CE, on-site test have been performed at Tunnel Stein in Carinthia, Austria, which is a part of the St. Kanzian tunnel chain, a section of the high-performance route Graz-Klagenfurt. The 2.1 km long tunnel is excavated using the principle of the NATM. Due to the geological conditions (loose rock and low overburden) a full face excavation is not feasible. Therefore, the construction is performed using a top heading-bench excavation with excavators mainly (see Figure 9.1). In the tunnel section where the connecting elements were tested a temporary top heading invert was installed. The overall constructional boundary conditions were identical to the on-site tests performed by Staudacher (2016).

Figure 7.1: Top heading-bench excavation of the Tunnel Stein.

The geometry of the CE illustrated in chapter 4.2.3 had been adapted to the site-specific conditions such as round length, shotcrete thickness, type of lattice girder and diameter of the connection reinforcement. In contrast to the final version of the CE, the used element had a vertical lug of 10 cm instead of 7 cm. L-shaped reinforcement bars (BSt 550) with a length of 80 cm and a diameter of 10 mm were used as connection reinforcement. The detailed design of the used CE is shown in Figure 7.2.

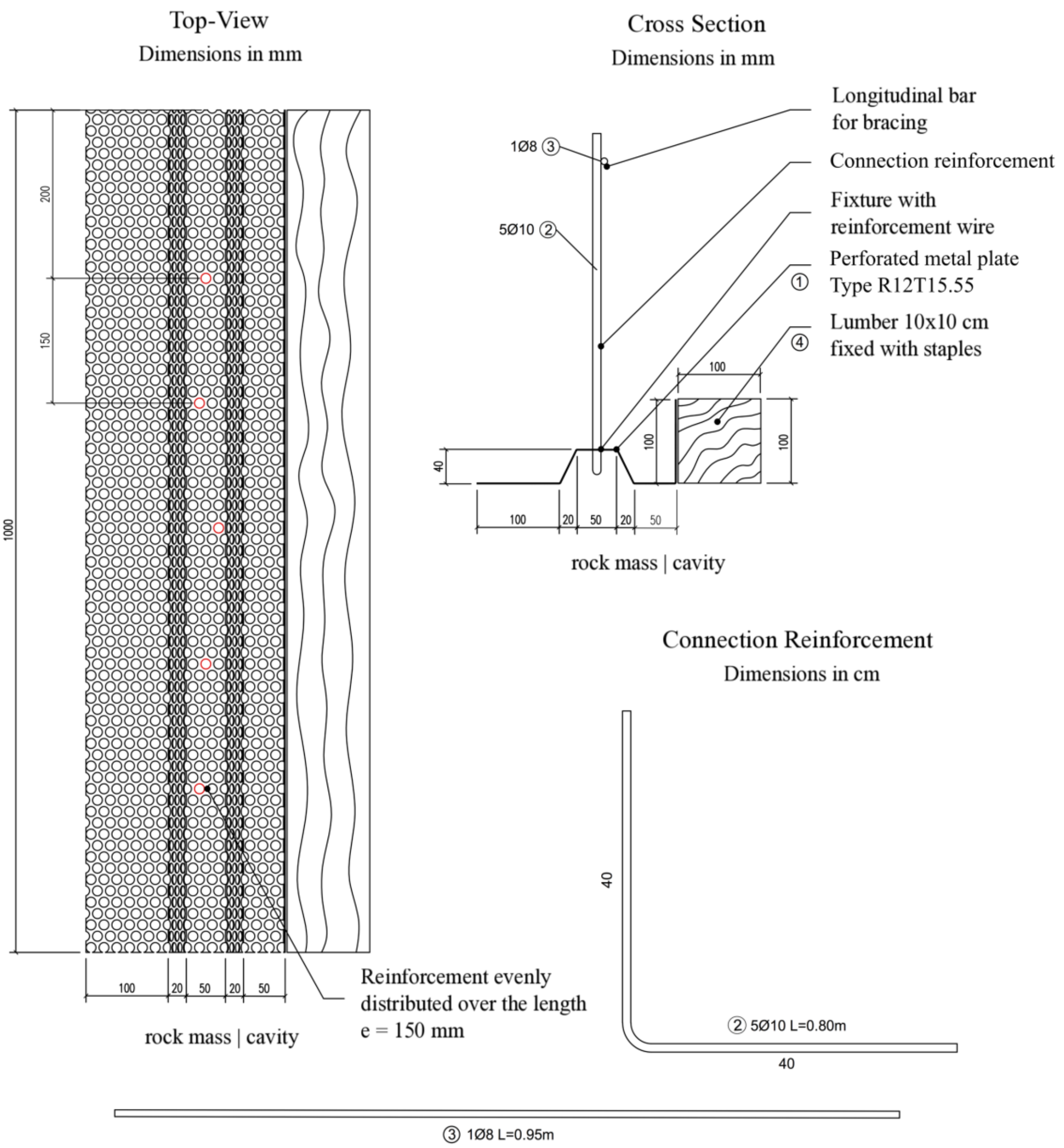


Figure 7.2: Geometry of the connecting element used on the construction site.

Since a temporary top heading invert was necessary in the cross-section of the testing area additional connection reinforcement bars (see Figure 9.3) had been attached for the connection of the shotcrete lining of the top heading and the temporary top heading invert. Small changes to the installation position were necessary as the connection reinforcement for the temporary top heading invert were not adapted to the use in combination with the CE. The reinforcement bars were placed horizontally on the upper side of the square timber. Five reinforcement bars were installed per round (1.30 m) with a distance of 15 cm.

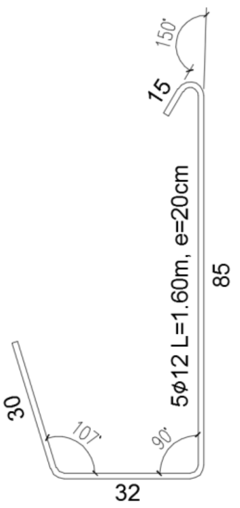


Figure 7.3: Connection reinforcement of the temporary top heading invert [dimensions in cm].

7.1 Construction sequence

The necessary working steps for a top heading-bench excavation as well as a top heading-bench excavation with a temporary top heading invert are described in more detail in and Appendix B. The individual work steps for each construction phase are displayed in red.

7.2 On-site installation of connecting element

Figure 7.4 shows the required on-site installation steps of the CE (Figure 7.2) and the connection reinforcement for a temporary top heading invert (Figure 7.3) at the Tunnel Stein. The individual working steps are described below:

(a) Shotcrete bench

In the first step a shotcrete bank is sprayed onto the excavation surface. It serves for the support and the correct positioning of the CE. Furthermore, a thin shotcrete layer is pre-sprayed to prevent falling rocks. Afterwards the outside reinforcement layer is installed.

(b) Placement of connecting element

The CE with the fixed square timber is placed on the shotcrete bench at the intended position. Afterwards, the connection reinforcement is fixed to the reinforcement steel mesh of the outside layer.

(c) Wooden wool

Wooden wool is inserted into the shear cleat to prevent the connection reinforcement from being covered with shotcrete.

(d) Connection reinforcement for temporary top heading invert

In the next step the connection reinforcement for the connection of the shotcrete lining of the temporary top heading invert is installed. The reinforcement bars are placed on the top of the square timber and fixed to the reinforcement steel mesh of the outside layer.

(e) Installed connecting element

The installed CE with the connection reinforcement for the temporary top heading invert can be seen.

(f) First layer of shotcrete lining

The first layer of the shotcrete lining of the top heading is sprayed.

(g) Final shotcrete lining

The final shotcrete lining of the top heading with the protruding connection reinforcement bars for the connection of the temporary top heading invert can be seen.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 7.4: Installation of the connecting element at Tunnel Stein.

In case of over-excavation in the invert area, the CE must be supported using bricks to ensure the correct installation position (Figure 7.5).

Figure 7.5: Installation of the connecting element in case of over-excavation.

The conclusions of the installation of the CE on-site are described below:

Installation of the connecting element

The installation per element takes approximately two minutes and can be installed by one miner with reinforcement wires and bricks only. Following criteria must be fulfilled during installation:

- Orientation of the CE with the vertical lug facing into the tunnel (twisted installation by 180° does not fulfill the requirements anymore)
- Preparation of a shotcrete bank as a base for the CE
- Installation of the CE at a maximum of 10 cm below the base plate of the lattice girder (over-excavation requires placement of bricks (max. 2 NF-bricks) below the CE)
- CE must be installed at approximately the same height for all rounds for an easier localisation of the element during bench excavation
- Length of the CE must be adapted to the round length at hand (shortening or overlapping as required)

- Insertion of wooden wool in shear cleat as protection for the connection reinforcement during shotcrete spraying.

Installation of the connection reinforcement for the temporary top heading invert

The installation time for the reinforcement bars for the connection of the temporary top heading invert is approximately five minutes and can be carried out by one miner. To facilitate the installation of the reinforcement bars they are placed on the square timber (Figure 7.4). Special care must be taken to ensure enough distance between the shotcrete lining to be produced and the upper end of the reinforcement. The upper end must not be covered with shotcrete during spraying. Therefore, a longitudinal reinforcement bar is used as a spacer.

Spraying of shotcrete

During spraying the stiff perforated metal plate resists the high pressures without larger deformations. The square timber and the vertical lug of the CE also contribute to a higher element stiffness. During spraying attention must be paid to possible shotcrete shadows, especially below and behind the element.

7.3 Temporary top heading invert

Following working steps are required for the construction in case of a temporary top heading invert (also see Figure 7.6). The improvements in the design of the temporary top heading invert (described in chapter 5) have already been considered in the on-site tests.

(a) Excavation of temporary top heading invert are

In the first step the temporary top heading invert area is excavated. Special care must be taken in the area of the CE to prevent damage.

(b) Removal of square timber

In the next step the square timber is removed from the CE. The removing must be done by hand. Removal using an excavation bucket may damage the element. The intended function of the element would therefore no longer exist.

(c) Exposed invert

The exposed invert can be seen.

(d) Bending down of connection reinforcement for temporary top heading invert

In the next step the connection reinforcement for the shotcrete lining of the temporary top heading invert is bent down. The rectangular notch, which was created by the square timber, facilitates this process and prevents damage to the shotcrete lining.

(e) Installation of reinforcement steel mesh for temporary invert

The reinforcement steel mesh for the shotcrete lining of the temporary top heading invert is installed.

(f) Application of fleece

To facilitate the later demolition of the shotcrete lining of the temporary invert, a fleece is installed as a separating layer between the shotcrete linings of the top heading and the temporary top heading invert. The height of the fleece is 1 m; the length relates to the excavation area. The bottom end of the fleece is positioned at the level of the connection reinforcement of the temporary invert. The fleece is fixed at the top on the protruding reinforcement steel mesh of the shotcrete lining of the top heading with reinforcement wire. On the bottom, the fleece is fixed to the reinforcement steel mesh for the temporary invert.

(g) Shotcrete lining of temporary top heading invert

In the next step the shotcrete lining of the temporary top heading invert is sprayed.

(h) Finished shotcrete lining of temporary top heading invert

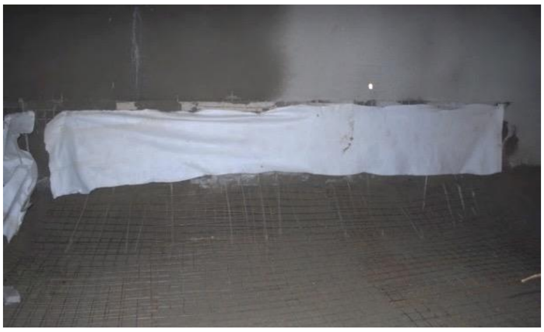
The finished shotcrete lining of the temporary top heading invert can be seen.

(a)

(b)

(c)

(d)

(e) (f)


(g) (h)

Figure 7.6: Production of a temporary top heading invert.

The conclusions of the production of the shotcrete lining of the temporary top heading invert are described in the following:

Removal of the square timber

The CE is exposed during the production of the temporary top heading invert in the area of the vertical lug. Figure 7.7 illustrates both the appropriate exposure and an example of an improper execution showing a damaged element. The damage to the element was mainly due to unawareness and/or carelessness of the workers and can be avoided. At the beginning of the on-site tests the square timber was removed using the excavator during excavation of the invert area for time reasons. This proved to be a fast method, but caused unnecessary destruction of the square timber and damage to the vertical lug (Figure 7.6 and Figure 7.7). The tests showed that the square timber must be removed by hand prior the excavation of the temporary top heading invert. To allow for a quick removal a cramp needs to be inserted into the square timber. Fastening the square timber using reinforcement wire caused damage to the vertical lug during removal of the square timber as the used wire withstands high forces. During the on-site tests, some lugs were accidentally bent down, which consequently lead to an improper function at the excavation of the bench as the predefined fracture surface was no longer present. To fulfil its proposed function the CE must remain undamaged (Figure 7.7 (a)). The necessary changes in the fixation method are already presented in chapter 4.2.

(a) Intended execution of the exposure of the connecting element.

(b) Inappropriate execution of the exposure of the connecting element.

Figure 7.7: Exposed connecting element during excavation of the temporary invert.

Bending down of the connection reinforcement

The 10 x 10 cm notch created by the square timber provides enough free space to bend down the connection reinforcement for the temporary top heading invert (Figure 7.6). Since the reinforcement bars, with the geometry of the CE used, rest exactly on the level of the edge of the vertical lug, it may happen that the lug is also bent downwards. To prevent this, the final version of the CE is designed with a shorter vertical lug, 7 cm instead of 10 cm. The size of the notch (10 x 10 cm) remains unchanged due to the dimensions of the square timber. The changes of the geometry are already described in chapter 4.2.3.

Installation of fleece

A further innovation in the design of the temporary top heading invert is the attachment of a fleece between the already existing shotcrete lining of the top heading and the temporary top heading invert and serves as a separating layer of the two shotcrete linings. The invert to be produced ranges over a length of four rounds (4 x 1.3 m). Therefore, the fleece is cut with 5-6 m in length and 1 m in height. Installation of the fleece on both sides requires approximately 10-15 minutes with the help of four miners. But one has to consider that the increased time exposure during installation can be saved at the removal of the temporary top heading invert and the excavation of the bench. The bottom end of the fleece is applied at the level of the connection reinforcement of the temporary top heading invert. The fleece is wired at the top on the protruding reinforcement steel mesh of the shotcrete lining of the top heading. On the bottom, the fleece is attached to the inserted reinforcement steel mesh for the temporary invert.

Spraying of shotcrete

During the spraying process, care must be taken that the fleece is fastened sufficiently to the reinforcement steel mesh on the bottom. Due to the high spraying pressure, it might be blown aside. To prevent the loosening of the fleece, spraying must start in the middle of the fleece. Only a small amount of shotcrete needs to be applied as it will be removed during bench excavation and only provides temporary backup (see chapter 5.2).

7.4 Excavation of the bench

Following working steps are required for the excavation of the bench (also see Figure 7.8):

(a) Demolition of shotcrete lining of temporary top heading invert

The shotcrete lining of the temporary top heading invert has to be demolished before the excavation of the bench.

(b) Excavation of the bench

In the next step the bench is excavated. During bench excavation, the CE is approached from below with great caution.

(c) Uncovering of the connecting element

At the excavation of the bench the CE has to be uncovered with the excavation bucket. The excavation bucket must never be placed above the CE to prevent any damage. The excavation is carried out just below the CE, after which the remaining material can be released by an impact of the excavator teeth.

(d) Uncovered connecting element

Figure 7.8 shows the uncovered CE and the connection joint thus created for the shotcrete lining of the bench.

(e) Connection reinforcement

The connection reinforcement for the shotcrete lining of the bench remains protected during the excavation in the trapezoidal shear cleat of the connecting element.

(f) Bending down of connection reinforcement

Before spraying of the shotcrete lining of the bench, the connection reinforcement is bent down out of the shear cleat of the CE.

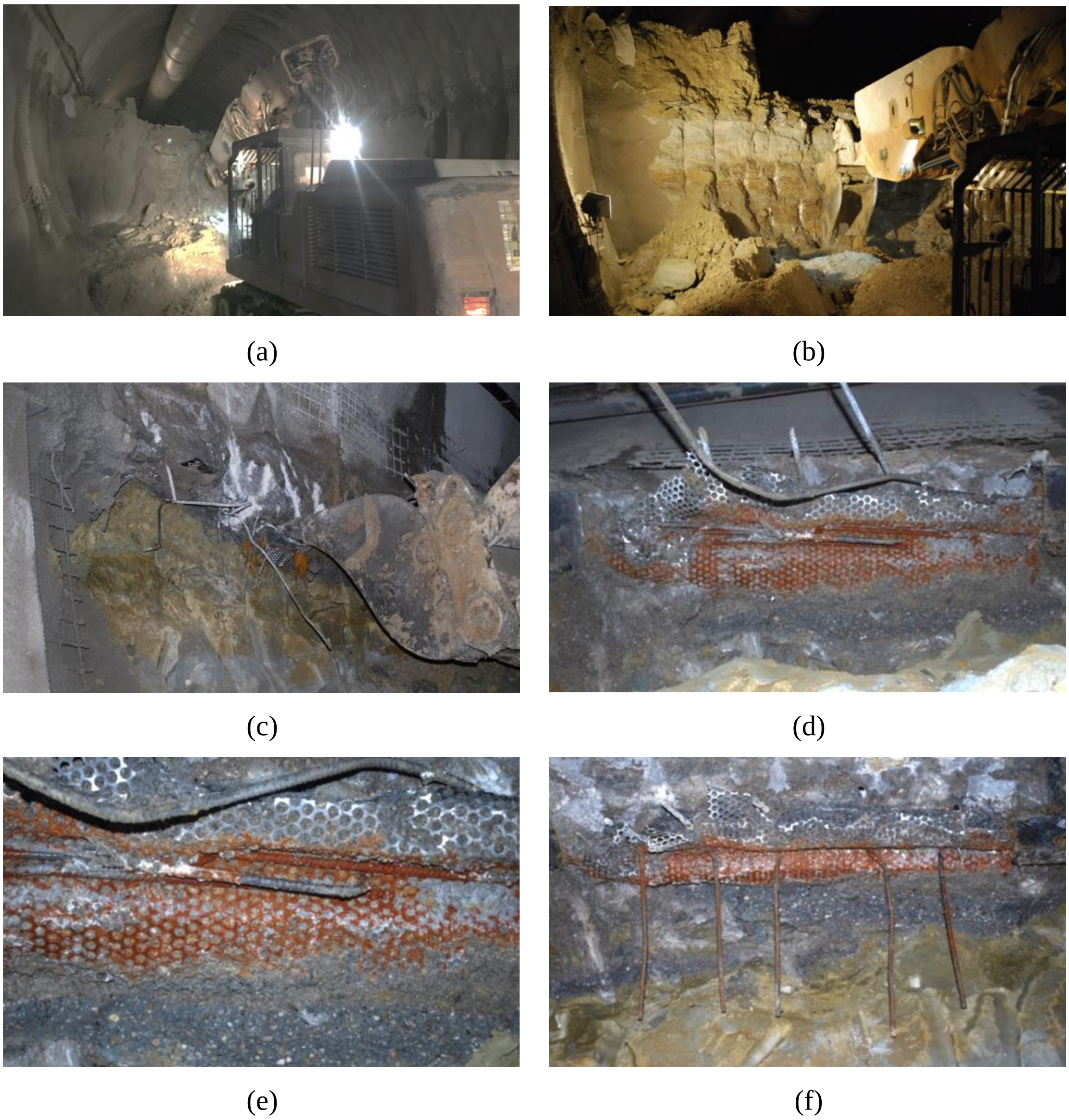


Figure 7.8: Excavation of the bench and removal of the concrete from the connecting element.

The conclusions of the excavation of the bench are described below:

Demolition of temporary invert

At the demolition of the shotcrete lining of the temporary top heading invert significant improvements in terms of working time and amount of work are shown. These result from the use of fleece as a separating layer between the shotcrete linings of the top heading and the temporary top heading invert. The shotcrete of the temporary top heading invert can be detached easily and quickly from the shotcrete lining of the top heading. It is possible to break up large fractions of the invert by simple tearing on the fleece with the excavation bucket. The reduced amount of concrete in the edge areas of the temporary invert also contribute to a facilitated demolition of the shotcrete lining of the invert and a saving in working time.

Uncovering of the connecting element

Several success factors are involved in the uncovering process of the CE during the excavation of the bench. A sufficient skill of the excavator driver is necessary above all for an ideal operation. The excavator driver must be aware of where he can position the excavation bucket and where he has to take special care during the excavation not to damage the CE. During the on-site tests, the excavation of the temporary invert caused occasional damage to individual vertical lugs of the CE, as seen in Figure 7.7 (b). These damages also affect the quality of the CE at later stages. If the lug is already covered with shotcrete in bent or damaged form during the production of the temporary top heading invert, the intended function as a separating surface is no longer fulfilled. The reasons of the damages as well as the resulting changes and improvements are described more in detail in chapter 4. Shortening of the vertical lug from 10 cm to 7 cm and fixation of the square timber using staples instead of reinforcement wire, as well as the removal of the square timber by hand, may prevent these damages almost completely.

Bending down of connection reinforcement

The connection reinforcement for the shotcrete lining of the bench is perfectly protected against the shotcrete of the top heading by the trapezoidal shear cleat of the CE and the wooden wool (Figure 7.8 (e)). There is a good accessibility to the individual reinforcement bars during connection to the reinforcement mesh of the bench. There is a very clear improvement compared to the rebending connectors of the field of structural engineering, which are normally used on the construction site of Tunnel Stein. Figure 7.8 (f) shows the already bent down connection reinforcement bars in impeccable condition.

7.5 Shotcrete lining of the bench

The working steps in the production of the shotcrete lining of the bench remain unchanged from the previous execution. The individual steps are illustrated in Figure 7.9 and described in the following:

(a) Pre-spraying of tunnel surface

A thin shotcrete layer is sprayed on the tunnel surface to prevent falling rocks.

(b) Installation of reinforcement steel mesh

The reinforcement steel mesh of the outside layer is installed. It is fixed to the bent-down connection reinforcement with reinforcement wire.

(c) Installation of lattice girder

In the next step the lattice girder is installed.

(d) Spraying of shotcrete lining

The shotcrete lining of the bench is sprayed.

(e) Final shotcrete lining

The final shotcrete lining of the bench can be seen.

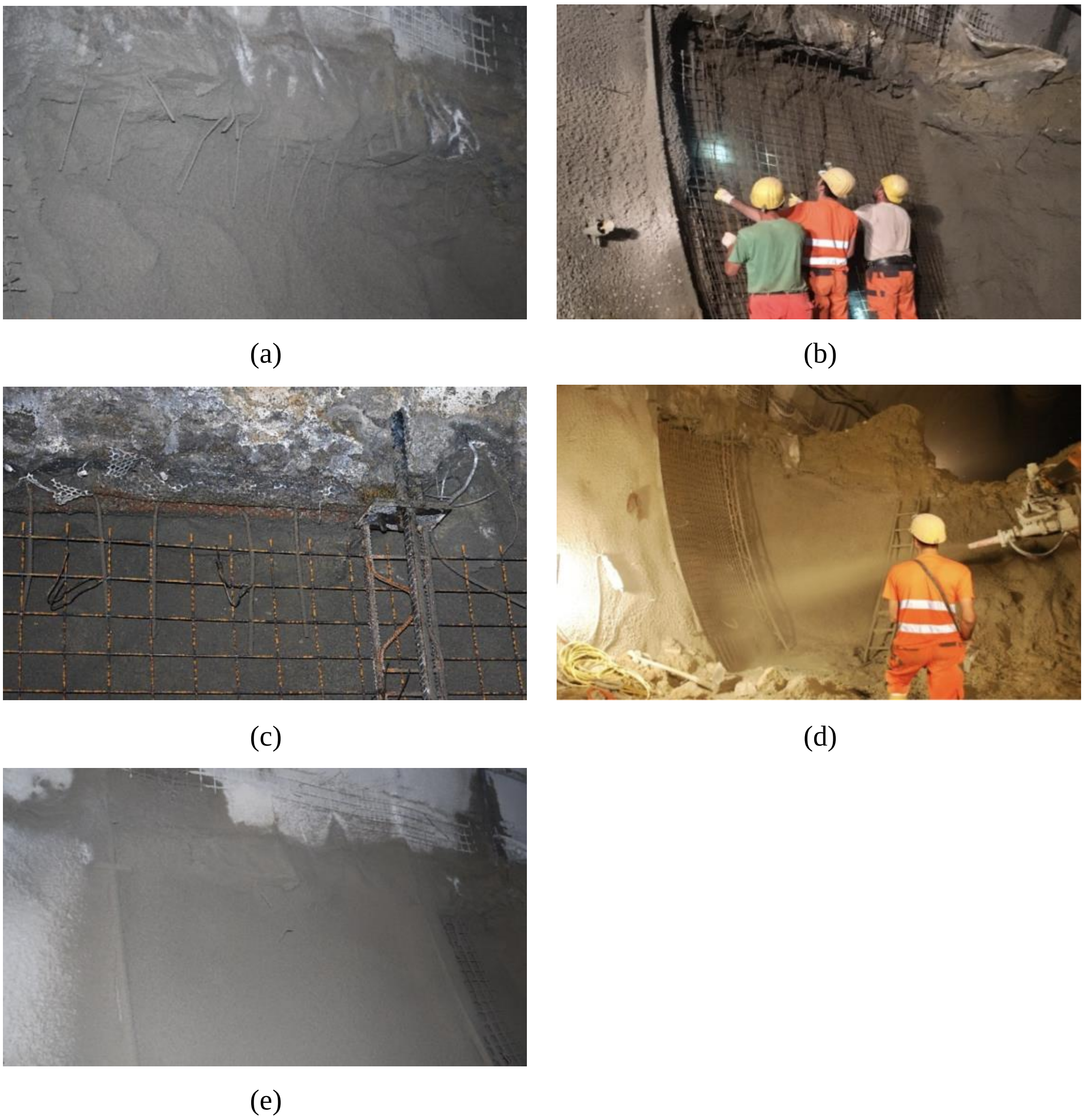


Figure 7.9: Production of the shotcrete lining of the bench.

7.6 Conclusions drawn from the on-site testing

The on-site tests showed that the use of the redesigned CE results in various advantages. If the partially encountered problems are corrected and the adaptions are executed as documented, a very good result will be achieved with the use of a CE. The main advantages are listed below:

- **Perforated metal plate as material for the connecting element:** The concrete can be easily removed from the CE. Furthermore, the 12 mm holes are well suited to install the connection reinforcement with a diameter of 10 mm in the CE.
- **Stiffer construction and material:** The stiffer construction and the stiffer material of the CE have proven itself. The stiffer construction prevents damage at the transportation and storage of the CE. Furthermore, during spraying of the shotcrete lining, the stiff perforated metal plate resists the high pressures without deformations.
- **Geometry of the connecting element:** The connection reinforcement for the shotcrete lining of the bench is perfectly protected against the shotcrete of the top heading by the shear cleat of the CE. The vertical lug helps to stiffen the CE.
- **Vertical lug of the connecting element:** The vertical lug of the CE contributes to a higher element stiffness. Furthermore, a separating layer is created between the shotcrete linings of top heading and temporary top heading invert which serves as a predetermined breaking point at the later demolition of the shotcrete lining of the invert.
- **Square timber as a closing strip:** The square timber allows for easier localisation of the CE in the shotcrete lining of the top heading, which in turn helps to prevent damage to the element. After removal of the square timber a notch is created in the shotcrete lining, which facilitates the further working steps. Furthermore, the square timber contributes to a higher stiffness of the CE. The reinforcement bars for the connection of the shotcrete lining of the temporary top heading invert can be placed on the top of the square timber. This allows a more comfortable installation of the connection reinforcement for the miners and simplifies the fixation to the outer reinforcement steel mesh.
- **Creation of a notch by the square timber:** The notch created helps the excavator driver to locate the CE before the excavation of the bench or the area of the temporary invert. The excavation bucket can be positioned in the notch. Furthermore, the notch provides enough free space to bend down the connection reinforcement for the temporary top heading invert.
- **Wooden wool:** The wooden wool prevents the connection reinforcement from being covered with shotcrete. In the final version the wooden wool is replaced by a pre-installed EPS strip on the bottom of the shear cleat.
- **Fleece as a aseparating layer:** Working time can be saved at the domolition of the shotcrete lining of the temporary top heading invert and the excavation of the bench. The shotcrete of the temporary top heading invert can be removed easily and quickly from the shotcrete lining of the top heading. It is possible to break up large fractions of the invert by simple tearing on the fleece with the excavation bucket.
- **Usage of less concrete:** The reduced amount of concrete in the edge areas of the temporary invert also contribute to a facilitated demolition of the invert and a saving in working time.

8 Costs of the connecting element

8.1 Comparison of costs

The listed costs of the CE made of perforated metal plate as well as expanded metal are based on an acceptance number of 1000 pieces. The costs include material costs and handling expenses (cutting, bending). For this purpose, the geometry of the CE from Staudacher (2016) was used. With the use of a perforated metal plate, a higher quality of the CE can be achieved, whereby the material price decreases at the same time. Construction management related influences are not taken into account. It can be seen that the costs for a single element made of perforated metal plate with a hole diameter of 12 mm is 1.25 € less compared to an element produced of expanded metal of type rhombus 10 x 5.

Table 8.1: Comparison of costs for one connecting element including bending work.

Version	Metal	Material	Type	Length [mm]	Thickness [mm]	Costs [€]
Wenger	perforated metal plate	mild steel 10.0330/DC01	R12T15.55	1000.00	1.00	6.75
Staudacher	expanded metal	mild steel galvanised	Rhombus 10 x 5	1000.00	1.00	8.00
					Difference	1.25

8.2 Costs of the connecting element “Wenger”

The costs for the redesigned CE with the dimensions shown in Figure 10.1 are given in Table 8.2. Again, the costs refer to an acceptance number of 1000 pieces. Thereby, the costs derive from a national sheet-metal processing company. The higher costs compared to the costs in Table 8.1 are related to the vertical lug of the element which requires more material and further edging. Also here, construction management related influences are not taken into account.

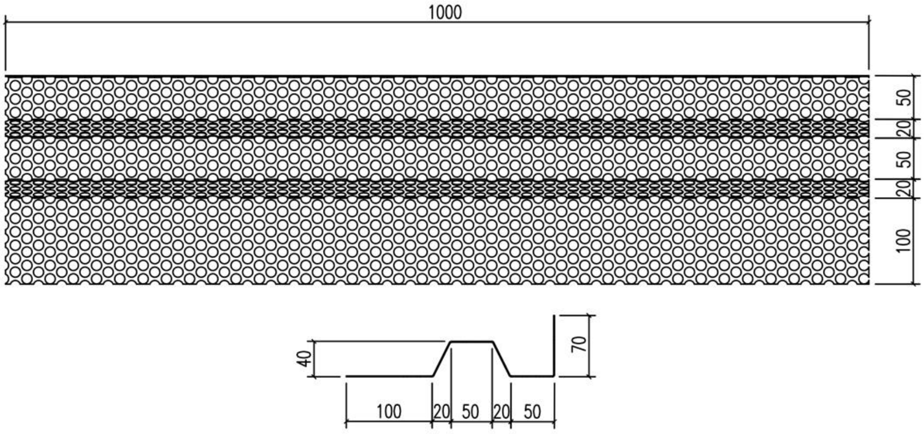


Figure 8.1: Dimensions of the connecting element “Wenger” [dimensions in mm].

Table 8.2: Costs of the connecting element “Wenger”.

Amount	Unit	Designation	Costs [€]
1	Pcs.	Connecting element Perforated metal plate type R12T15.55 Material: mild steel 1.0330 / DC01 Length: 1,000.00 mm Thickness: 1.00 mm Incl. bending work	13.00

Table 8.3 lists the costs of the CE in neighbouring countries. The costs contained therein are derived from official price requests. The cheapest offeror is Michael KFT Sheet Metal Processing, based in Hungary with a net price of 6.06 € per piece.

Table 8.3: Costs of the connecting element in different countries.

Country	Company	Costs [€]
Austria	Schatzdorfer Gerätebau	13.00
Hungary	Michael KFT Sheet Metal Processing	6.06
	Melior Laser	9.93
	Prospera Europe Kft	7.35
Poland	Pagwa	9.92
	Techmark	7.50
Slovenia	Intec MKD	11.80

9 Conclusion

With the use of the CE of Staudacher (2016) for the connection of the shotcrete linings of top heading and bench, good results have already been achieved. However, the on-site tests revealed potential for improvement. The research at hand showed an optimisation of the CE of version "Staudacher" (Staudacher, 2016) and a development of a production-ready version using an perforated metal plate as a separating layer. Besides the use of a stiffer material, adaptions of the geometry of the element as well as its installation were carried out. The necessary reinforcement for the connection of the shotcrete linings is, as in version "Staudacher" (Staudacher, 2016), hidden in a trapezoidal recess called shear cleat and is bent downwards after the excavation of the bench.

General advantages when using a connecting element

Removal of the shotcrete from the perforated metal plate provides a clean and planar surface which gives access to the incorporated connection reinforcement and eliminates subsequent mechanical removal of the shotcrete. The amount of work at the excavation of the bench and the following work steps is thereby reduced and thus costs can be saved. Furthermore, due to the planar and clean (barely shotcrete rebound and outbreak material) connection joint as well as a continuous reinforcement the static requirements are fulfilled.

Advantages to the version "Staudacher"

The advantages of the optimised CE are reflected in the much higher stiffness with lower weight as well as in a higher maximum transferable shear force and a better removability of the concrete. The stiffer construction greatly facilitates assembly, transport and the installation as well as the spraying process. Another great advantage is the lower material price. However, it should be noted that the version "Wenger" is slightly more expensive than the version "Staudacher" (Staudacher, 2016) due to the additional vertical lug of the element. The optimised version of the CE has static, economic and construction management advantages.

As an aid for locating the CE, a square timber is attached on the cavity-side of the element during the spraying of the shotcrete, resulting in a continuous and clearly visible notch in the shotcrete lining of the top heading. Furthermore, the square notch facilitates the downward-bending of the connection reinforcement for the shotcrete lining of the temporary top heading invert. Another advantage is the additional stiffening of the element during installation and spraying.

Furthermore, improvements have been made to the previous design of a temporary top heading invert. The new version includes the use of the optimised CE as well as a reduction of material, working time and costs. The advantages of the CE are also reflected in conjunction with a temporary top heading invert. In order to facilitate the later demolition of the temporary invert, a fleece is embedded as a separating layer of the shotcrete linings of top heading and temporary top heading invert. Due to the revision of the previous design, both material and working time can be saved. By using the CE and the fleece as separating layers, the work steps for the workers on the construction site are made much easier.

The result of the work carried out was considered to be very positive in the course of the on-site tests by both the construction company and the construction supervision. The CE as well as the corresponding adaptions of the design and work steps should be included in the design for following tunnel projects using top heading-bench excavation. If the problems resulting from the on-site tests are rectified as described, an impeccable function of the CE can be achieved. A subsequent series production can thus be sought. The developed CE can be adapted to different tunnel projects by few changes in the geometry and the dimensions. Following parameters need to be adapted for a single tunnel drive:

- Length of the element: Variation of the length for different round lengths
- Wide of the element: Variation of the wide for different thickness of the shotcrete lining
- Hole diameter of the perforated metal plate: Variation of the hole diameter for different diameters of the connection reinforcement
- Thickness of the perforated metal plate: Variation of the thickness to increase the stiffness of the CE

In order to achieve the desired function of the CE, above all the awareness of the workers is of great importance.

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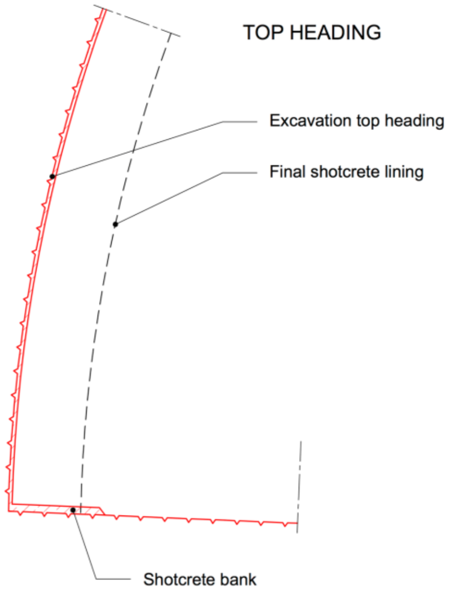
Appendix A

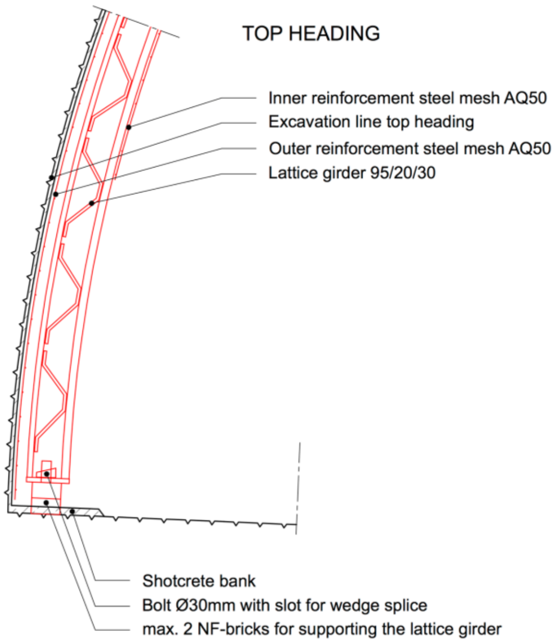
Construction sequence – Top heading-bench excavation

1) Excavation Top Heading + Production Shotcrete Bank



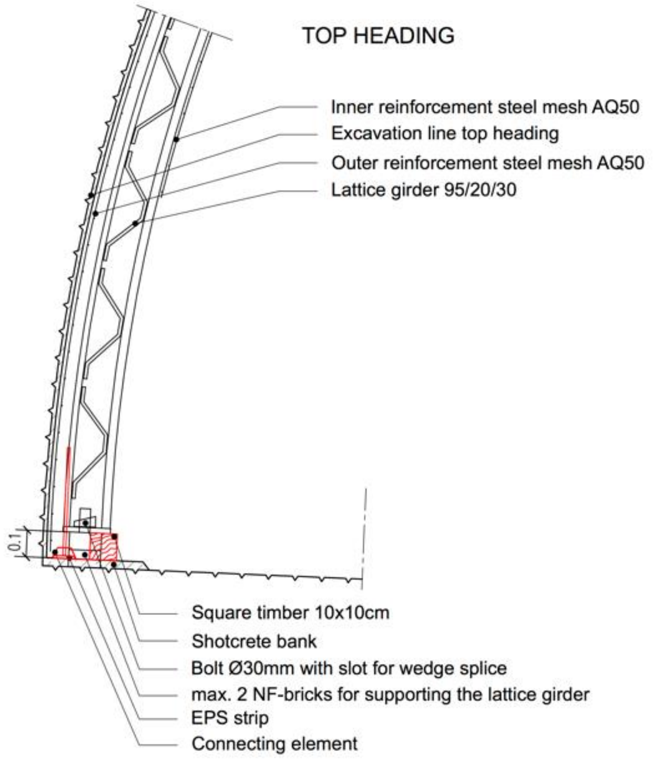
Working Steps:
- Excavation of the top heading
- Pre-spraying of the tunnel surface
- Production of a shotcrete bank for supporting the connecting element

2) Installation Lattice Girder + Reinforcement Steel Mesh



Working Steps:
- Installation of outer reinforcement steel mesh, fixing to lattice girder, do NOT place on invert
- Installation of lattice girder; supported by max. 2 NF-bricks
- Installation of inner reinforcement steel mesh

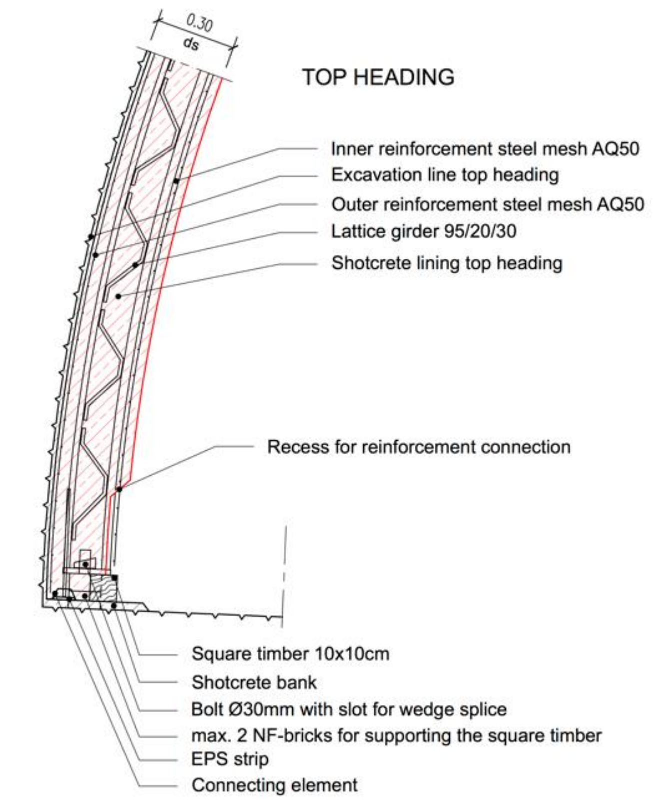
3) Installation Connecting Element



Working Steps:

- Installation of the connecting element with fixed square timber; placing the element on the pre-sprayed shotcrete bank at a maximum distance of 10cm below base plate of lattice girder, if this is not possible, element must be positioned on bricks, connection reinforcement must be located at the outer side of the lattice girder
- Fixing the connection reinforcement to the outer reinforcement steel mesh

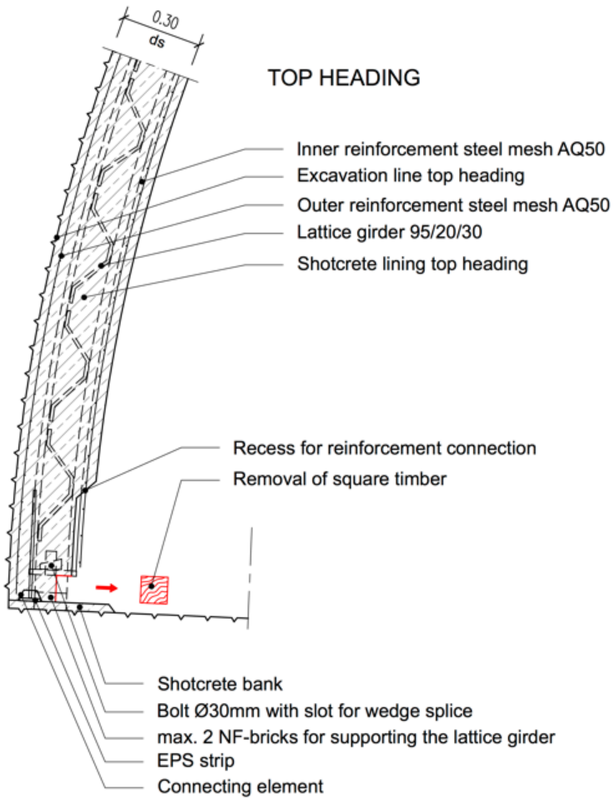
4) Production Shotcrete Lining Top Heading



Working Steps:

- Production of shotcrete lining of top heading, 1. layer
- Carefully backfilling of the connecting element from the top with shotcrete; if connecting element is placed on bricks, first spraying from underneath

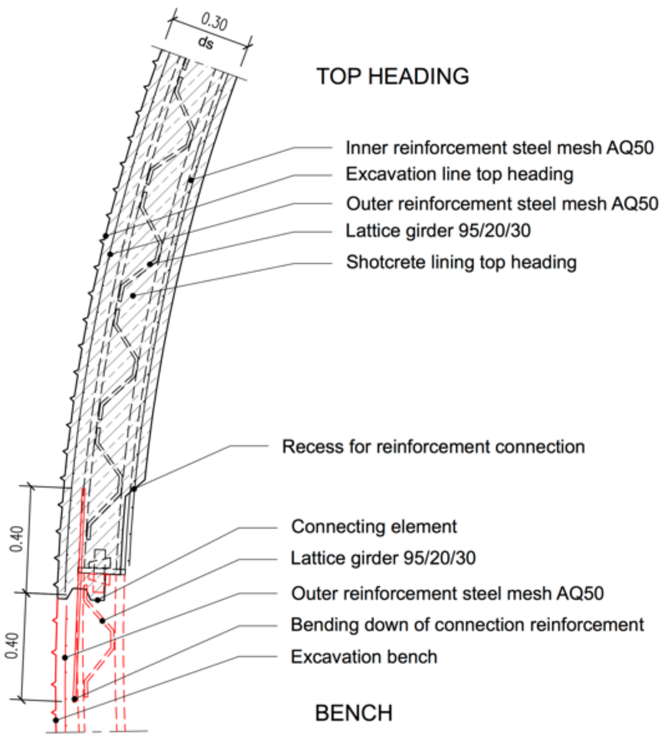
5) Removal of Square Timber



Working Steps:

- Removal of the square timber
- To avoid damage to the connecting element and the square tumber itself, intended to be removed by hand; square timber must be released from shotcrete by a jackhammer first
- A pick is hooked in the driven cramp to rip off the square timber from the shotcrete lining

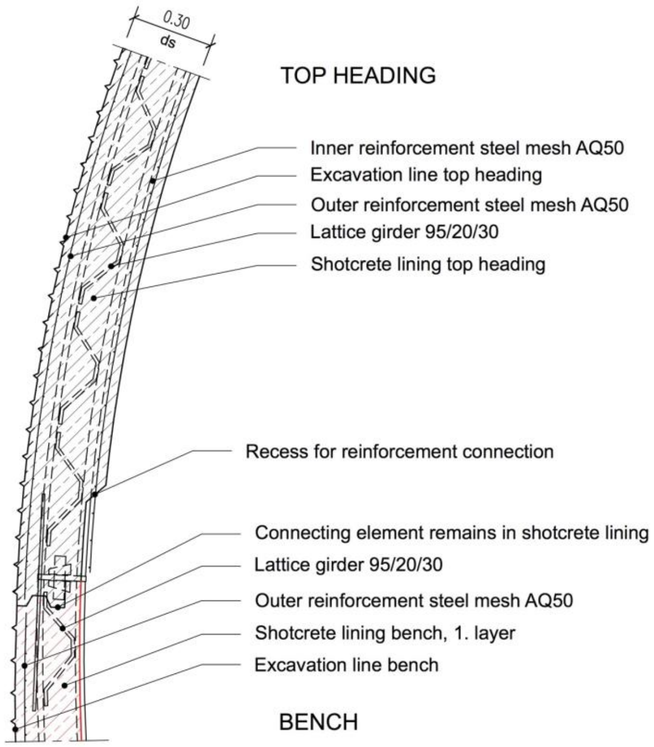
6) Excavation Bench + Reinforcement Steel Mesh + Lattice Girder + Bending Down Reinforcement



Working Steps:

- Demolition of shotcrete lining of temporary top heading invert
- Excavation of bench
- Installation of outer reinforcement steel mesh of bench, Installation of lattice girder
- Bending down of connection reinforcement for shotcrete lining of bench

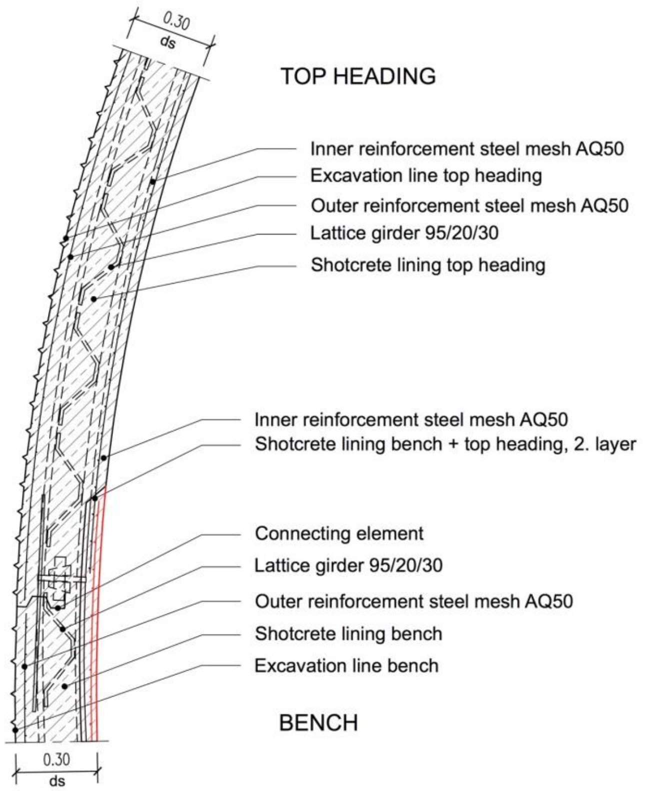
7) Production Shotcrete Lining of Bench



Working Steps:

- Production of shotcrete lining of bench, 1. layer

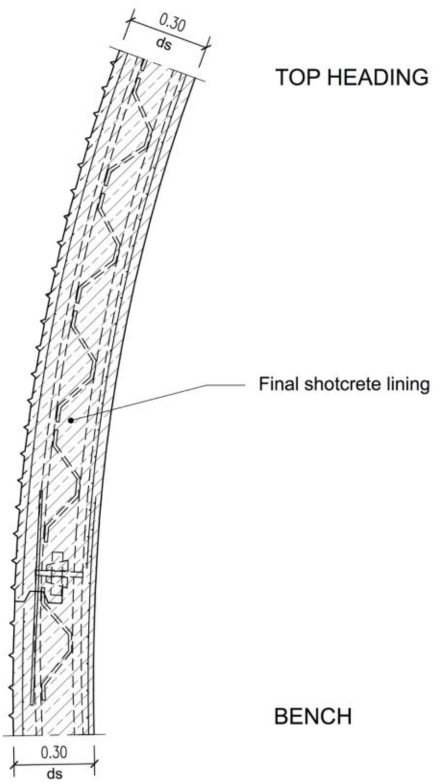
8) Shotcrete Lining 2. Layer, Top Heading + Bench



Working Steps:

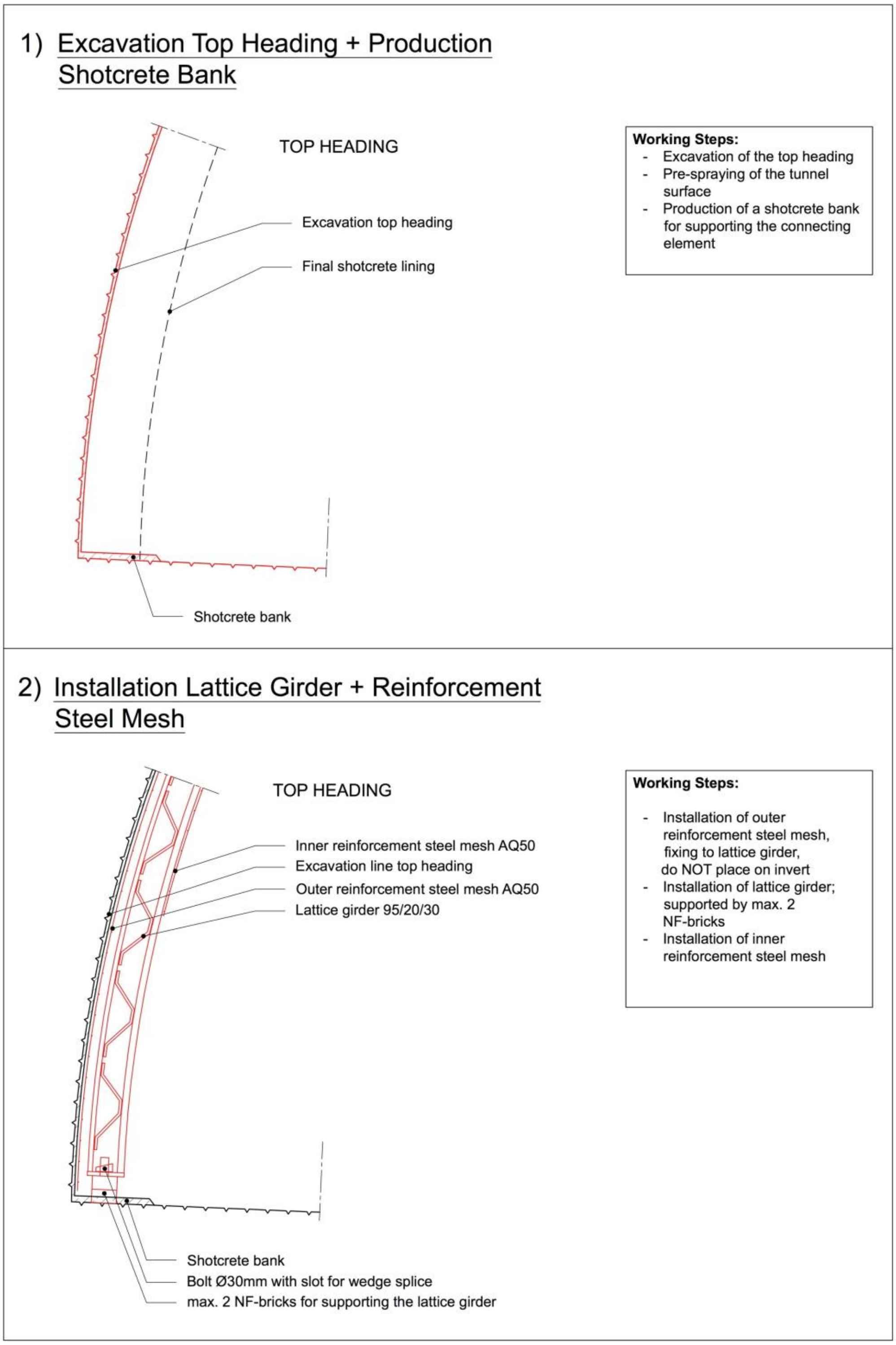
- Installation of inner reinforcement steel mesh, top heading and bench
- Production of shotcrete lining of top heading and bench, 2. layer

9) Final State

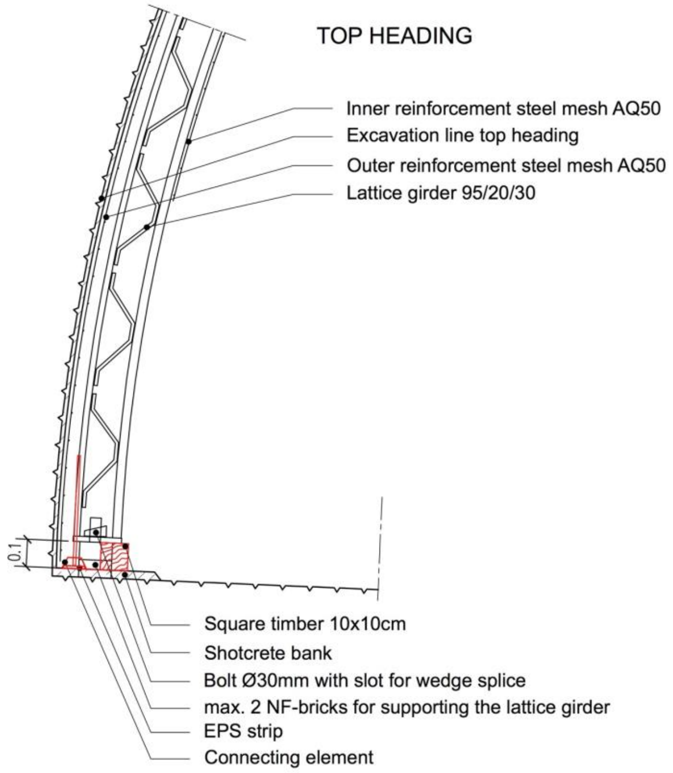


Appendix B

Construction sequence – Top heading-bench excavation with temporary top heading invert



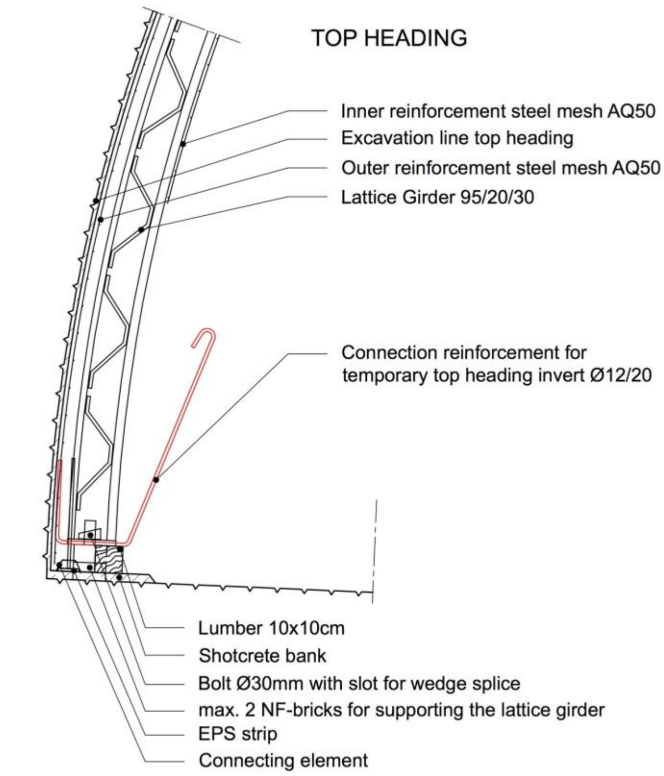
3) Installation Connecting Element



Working Steps:

- Installation of the connecting element with fixed square timber; placing the element on the pre-sprayed shotcrete bank at a maximum distance of 10cm below base plate of lattice girder, if this is not possible, element must be positioned on bricks, connection reinforcement must be located at the outer side of the lattice girder
- Fixing the connection reinforcement to the outer reinforcement steel mesh

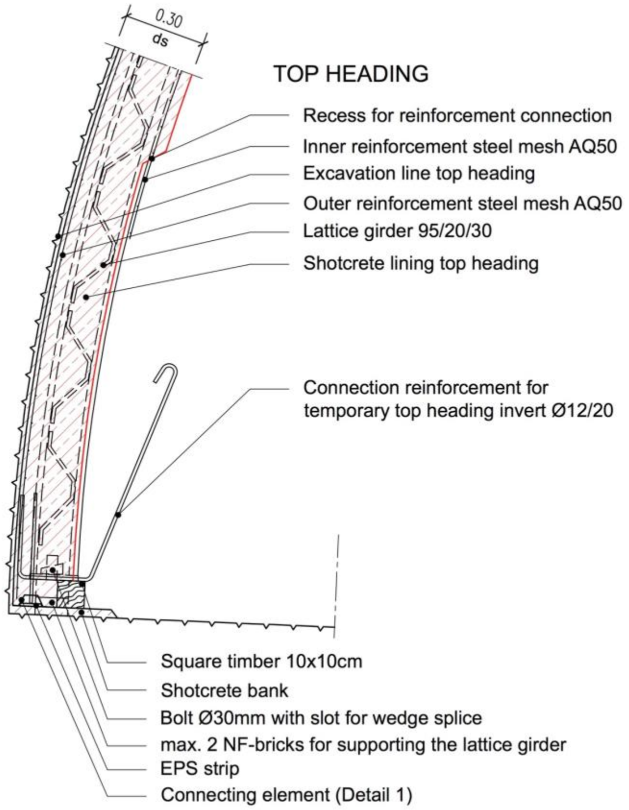
4) Installation Connection Reinforcement for Temporary Top Heading Invert



Working Steps:

- Installation of connection reinforcement for temporary top heading invert; pushed from the front through the outer reinforcement steel mesh and placed on top of lumber
- Fixed to the outer reinforcement steel mesh

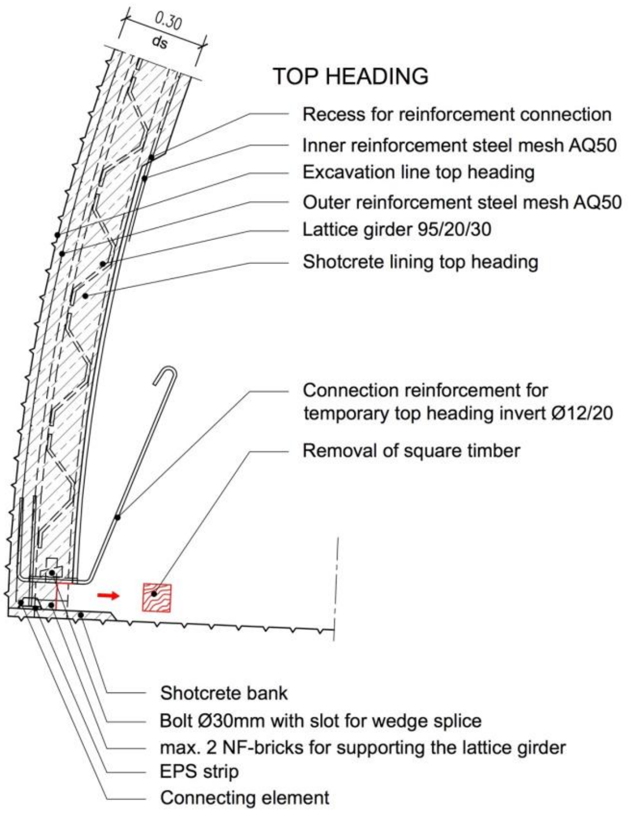
5) Production Shotcrete Lining Top Heading



Working Steps:

- Production of shotcrete lining of top heading, 1. layer
- Carefully backfilling of the connecting element from the top with shotcrete; if connecting element is placed on bricks, first spraying from underneath

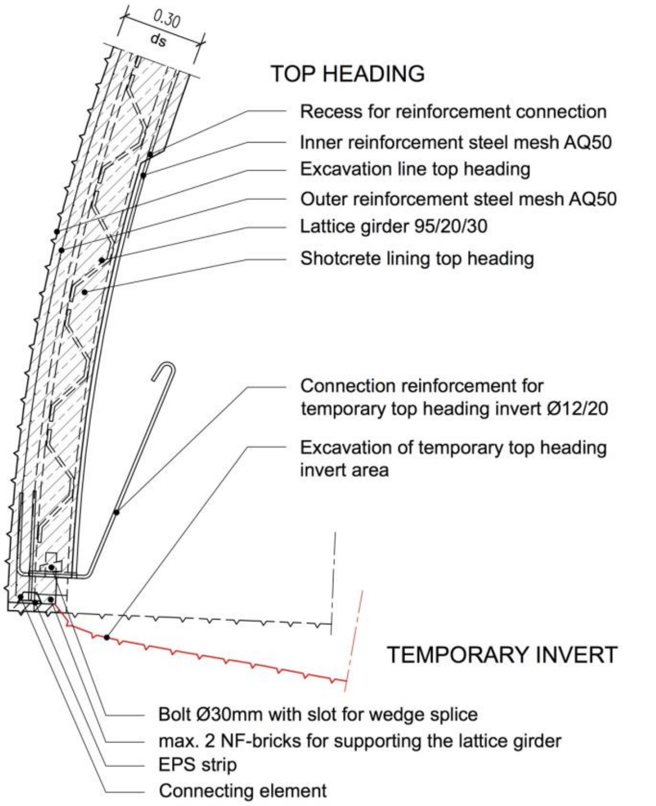
6) Removal of Square Timber



Working Steps:

- Removal of square timber
- To avoid damage to the connecting element and the square timber itself, intended to be removed by hand; square timber must be released from shotcrete by a jackhammer first
- A pick is hooked in the driven cramp to rip off the square timber from the shotcrete lining

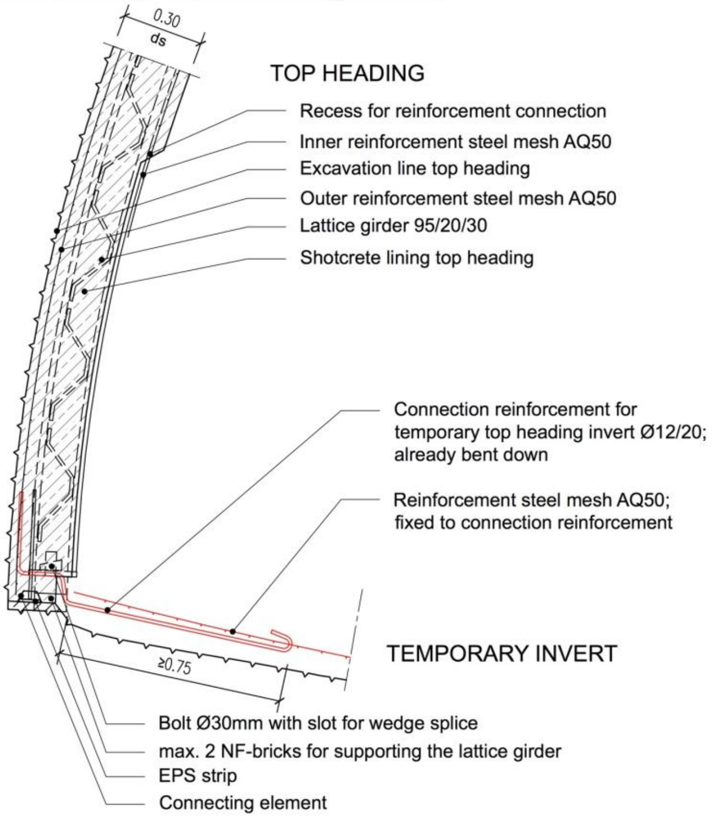
7) Excavation of Temporary Top Heading Invert



Working Steps:

- Excavation of temporary top heading invert area; area below connecting element is not excavated
- Special care in the area of the vertical lug of the connecting element; should remain undamaged for later functions

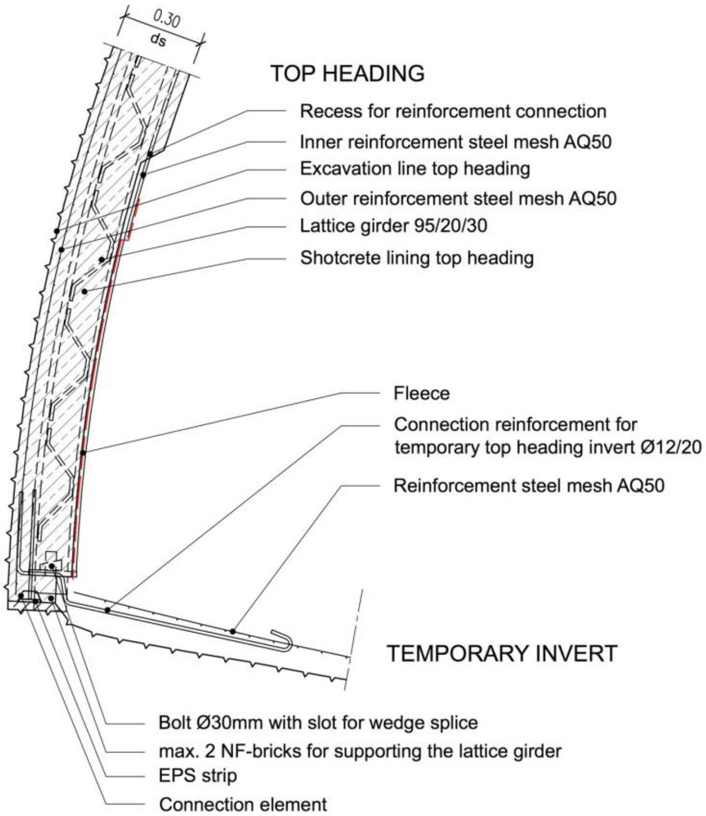
8) Installation Connection Reinforcement for Temporary Top Heading Invert



Working Steps:

- Bending down of connection reinforcement for temporary top heading invert
- Installation of reinforcement steel mesh for invert

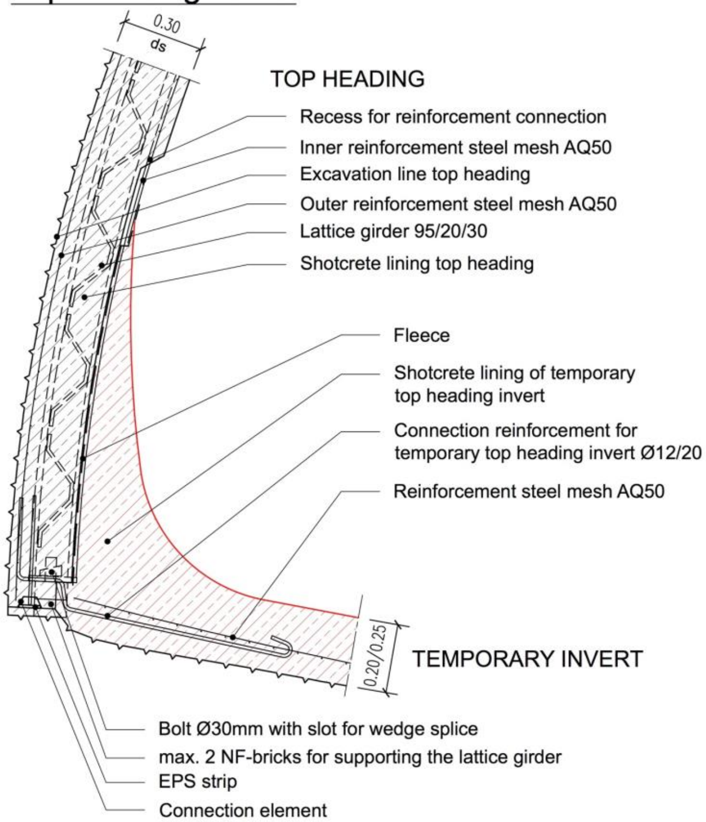
9) Installation of Fleece



Working Steps:

- Installation of fleece to the existing shotcrete lining
- Bottom end of fleece is positioned at level of connection reinforcement of temporary invert
- Fixed with reinforcement wire at the top to protruding reinforcement steel mesh of shotcrete lining of top heading, at the bottom fixed to reinforcement steel mesh for invert

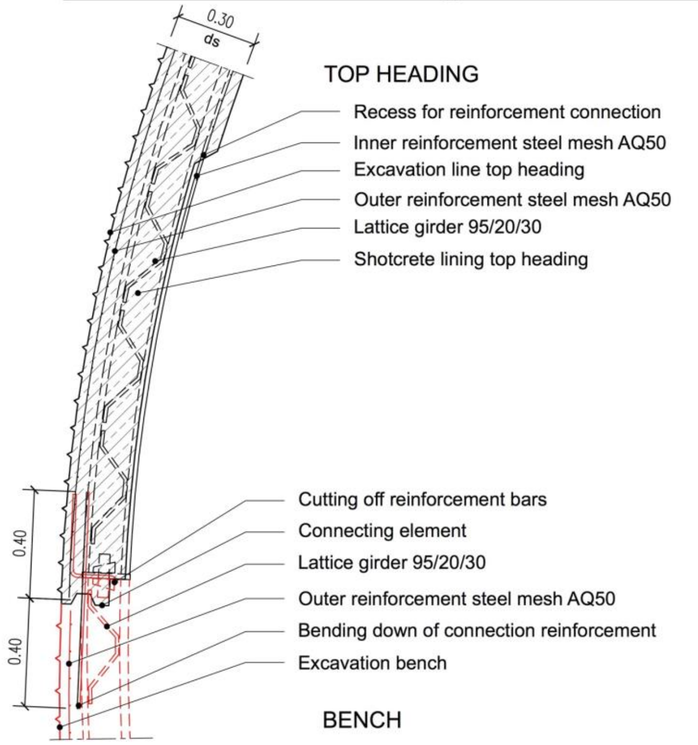
10) Production Shotcrete Lining of Temporary Top Heading Invert



Working Steps:

- Production of shotcrete lining of temporary top heading invert
- Excessive shotcrete application should be avoided
- Spraying up to close to upper end of fleece

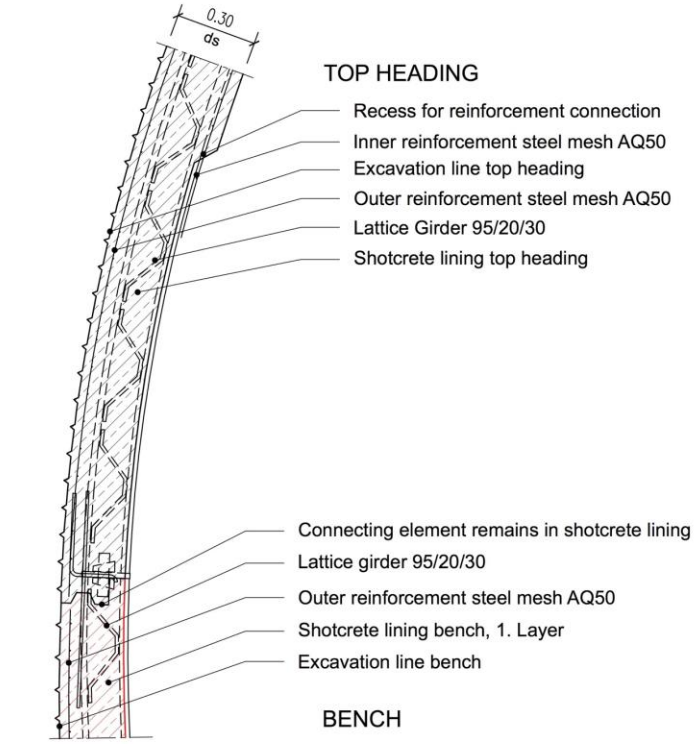
11) Excavation Bench + Reinforcement Steel Mesh + Lattice Girder + Bending Down Reinforcement



Working Steps:

- Demolition of shotcrete lining of temporary top heading invert
- Excavation of bench
- Cutting off reinforcement bars of invert
- Installation of outer reinforcement steel mesh of bench
- Installation of lattice girder
- Bending down of connection reinforcement for shotcrete lining of bench

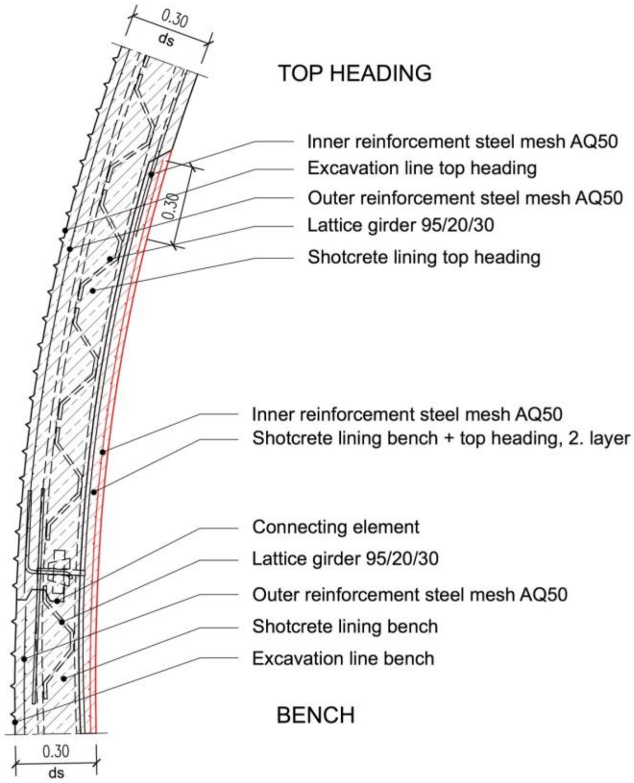
12) Production Shotcrete Lining of Bench



Working Steps:

- Production of shotcrete lining of bench, 1. layer

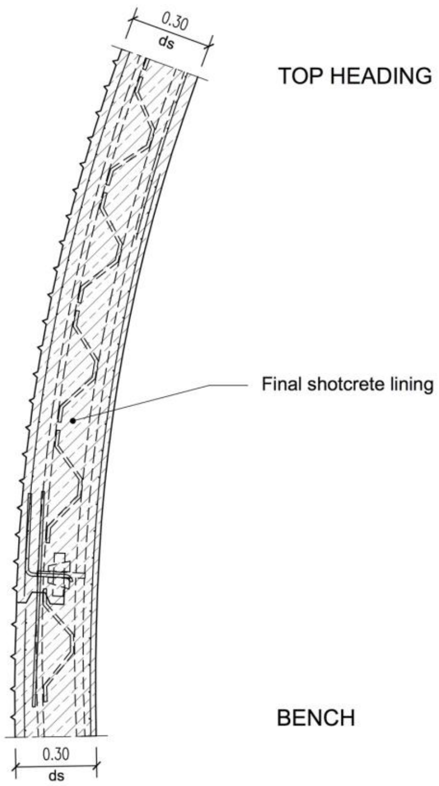
13) Shotcrete Lining 2. Layer, Top Heading + Bench



Working Steps:

- Installation of inner reinforcement steel mesh, top heading and bench
- Production of shotcrete lining of top heading and bench, 2. layer

14) Final State



Appendix C

Datasheet of the fleece Drefon RVS 3850-1

The following datasheet for a fleece of type Drefon RVS 3850-1 from the company Manifattura Fontana (Italy) (2014) was submitted from the company Dapek Dach- und Abdichtungstechnik GmbH (Austria).

Declaration of Performance

DoP n°: Drefon RVS 3850-1 - 2014.09.01

1. Product Name and 2. Product Type

Drefon RVS 3850-1

100% Polypropylene Nonwoven Geotextile

3. Intended use

For	Application	Functions	For	Application	Functions
Roads		Filtration Separation Drainage	Reservoirs and dams		Filtration Separation
Railways		Filtration Separation Drainage	Canals		Filtration Separation
Foundations and walls		Filtration Separation Drainage	Tunnels		/
Drainage systems		Filtration Separation Drainage	Solid waste disposals		Filtration Separation
Erosion control		Filtration Separation Drainage	Liquid waste disposals		Filtration

4. Registered trade name MANIFATTURA FONTANA GEOTESSILI NONTESSUTI

5. Contact address Via Fontoli, 10 - 36020 Valstagna - Italy
Tel: +39 0424 99896 - Fax: +39 0424 99827
www.manifatturafontana.net

6. AVCP System 2+

7. Notified body 1213

EN 13249:2014 EN 13250:2014 EN 13251:2014 EN 13252:2014 EN 13253:2014
EN 13254:2014 EN 13255:2014 EN 13256:2014 EN 13257:2014 EN 13265:2014

Notified body SKZ – TeConA GmbH (identification no. 1213) performed the initial inspection of the manufacturing plant and of factory production control (FPC) and the continuous surveillance, assessment and evaluation of FPC and issued the certificate of conformity of the FPC n° 3243.

8. Declared performance

Essential characteristics		Performance: Mean value		Tolerance		Standard	Harmonised Technical Specifications
Tensile strength	CMD	27,1	kN/m	-2,4	kN/m	EN ISO 10319	EN 13249:2014 EN 13250:2014 EN 13251:2014 EN 13252:2014 EN 13253:2014 EN 13254:2014 EN 13255:2014 EN 13256:2014 EN 13257:2014 EN 13265:2014
	MD	25,4	kN/m	-2,1	kN/m		
Elongation at maximum load	CMD	75	%	± 11	%	EN ISO 10319	
	MD	75	%	± 11	%		
Static puncture (CBR test)		4.100	N	-250	N	EN ISO 12236	
Dynamic perforation (Cone drop test)		12,5	mm	1,5	mm	EN ISO 13433	
Pyramid Puncture		-	N	-	N	EN 14574	
Characteristic opening size		100	μm	± 20	μm	EN ISO 12956	
Water permeability normal to the plane		68	$l/(s\ m^2)$	-16	$l/(s\ m^2)$	EN ISO 11058	
Water flow in the plane	20 kPa, i=1	6,5	$*10^{-6}\ m^2/s$	-2,3	$*10^{-6}\ m^2/s$	EN ISO 12958	
Weathering resistance	To be covered within 1 month after installation					EN 12224	
Oxidation resistance	Durable in natural soil with phH < 4 or > 9 and soil temperature > 25 °C for a minumum of 50 year service life (EN 12225 e EN 14030 A/B)					EN ISO 13438 met A	
Dangerous substances	Less than required by national regulations in EU Member States						

9. Declaration

The performance of the product identified in points 1 and 2 is in conformity with the declared performance in point 8.
This declaration of performance is issued under the sole responsibility of the manufacturer identified in point 4.

Signed for and on behalf of the manufacturer by:

Francesco Fontana - Sole administrator
(name and function)

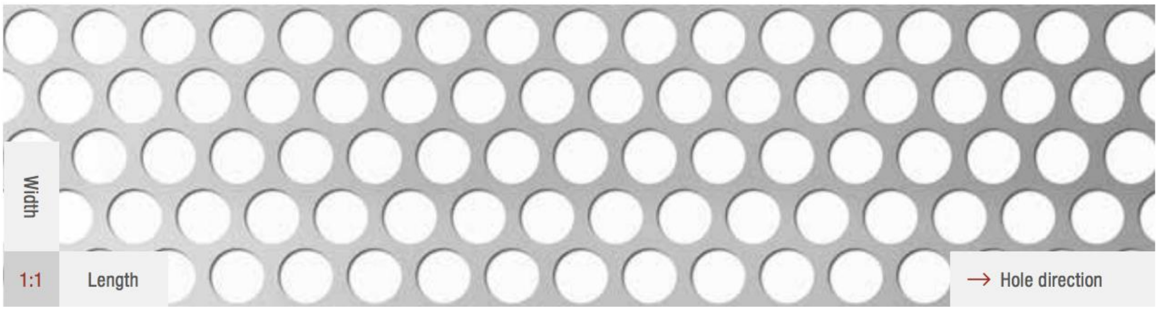
Valstagna, 01.09.2014
(place and date of issue)

(signature)

Appendix D

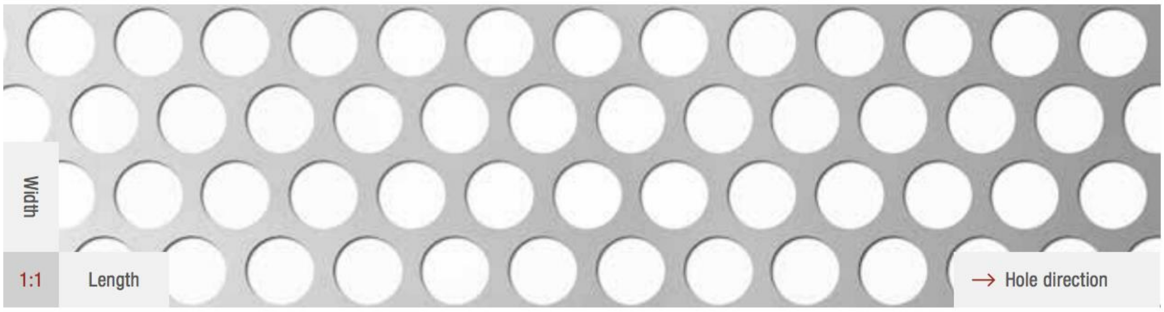
Datasheet of the perforated metal plates

The following datasheets for the used perforated metal plates derive from the RMIG Express Catalogue “Standard perforated and expanded metal sheets for quick delivery” of the company RMIG Ltd. (United Kingdom) (2017).



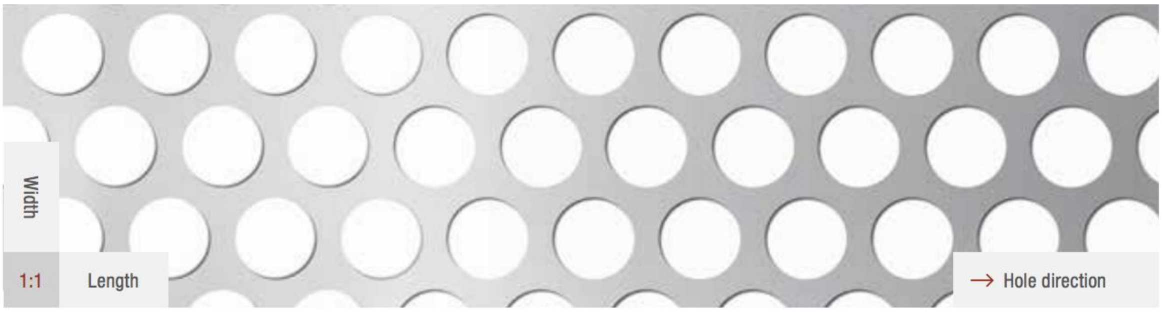
R8T10	Hole R = 8	Pitch T = 10	Bridge B = 2	Open area 58.0 %

Material	Thickness mm	1000 x 2000 mm	1250 x 2500 mm	1500 x 3000 mm	Kg/m²
Mild steel	1.00	SMJ0800	SMJ0801		3.4
	1.25	SMKE0800	SMKE0801	SMKE0802	4.2
	1.50	SHL0800	SHL0801		5.0
	2.00	SHP0800	SHP0801	SHP0802	6.7
	2.50	SHQ0800	SHQ0801	SHQ0802	8.4
	3.00	SHR0800	SHR0801	SHR0802	10.1
Sendzimir galvanised (DX51D)	0.70		SGG0801		2.5
	1.00	SGJ0800	SGJ0801	SGJ0802	3.4
	1.25	SGKE0800	SGKE0801	SGKE0802	4.2
	1.50	SGL0800	SGL0801	SGL0802	5.0
	2.00	SGP0800	SGP0801	SGP0802	6.7
	3.00	SGR0800	SGR0801	SGR0802	10.1
Aluminium EN 1050	1.00	SAJ0800	SAJ0801	SAJ0802	1.1
	1.50	SAL0800	SAL0801	SAL0802	1.7
	2.00	SAP0800	SAP0801	SAP0802	2.3
Stainless steel EN 1.4301 (AISI 304)	1.00	SSJ0800	SSJ0801	SSJ0802	3.4
	1.50	SSL0800	SSL0801	SSL0802	5.0
	2.00	SSP0800	SSP0801	SSP0802	6.7
Stainless steel EN 1.4404 (AISI 316L)	1.00	SXJ0800	SXJ0801		3.4
	1.50	SXL0800	SXL0801		5.0
	2.00	SXP0800			6.7



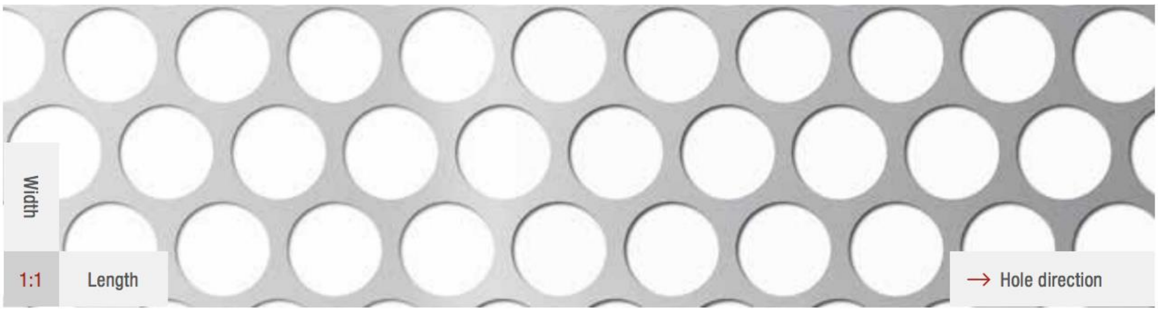
R10T12.7	Hole R = 10	Pitch T = 12.7	Bridge B = 2.7	Open area 56.2 %

Material	Thickness mm	1000 x 2000 mm	1250 x 2500 mm	1500 x 3000 mm	Kg/m²
Mild steel	1.00	SMJ1000	SMJ1001		3.6
	1.50	SHL1000	SHL1001		5.4
	2.00	SHP1000	SHP1001	SHP1002	7.2
	2.50	SHQ1000	SHQ1001	SHQ1002	8.8
	3.00	SHR1000	SHR1001	SHR1002	10.5
Sendzimir galvanised (DX51D)	1.00	SGJ1000	SGJ1001		3.6
	1.50	SGL1000	SGL1001		5.4
	2.00	SGP1000	SGP1001		7.2
Stainless steel EN 1.4301 (AISI 304)	1.00	SSJ1000	SSJ1001		3.6
	1.50	SSL1000	SSL1001		5.4
	2.00	SSP1000	SSP1001		7.2



R12T15.55	Hole R = 12	Pitch T = 15.55	Bridge B = 3.55	Open area 54.0 %

Material	Thickness mm	1000 x 2000 mm	1250 x 2500 mm	1500 x 3000 mm	Kg/m²
Mild steel	1.00	SMJ1200	SMJ1201		3.8
	1.25	SMKE1200	SMKE1201		4.6



R14T16.5	Hole R = 14	Pitch T = 16.5	Bridge B = 2.5	Open area 65.3 %

Material	Thickness mm	1000 x 2000 mm	1250 x 2500 mm	1500 x 3000 mm	Kg/m²
Mild steel	1.00	SMJ1400	SMJ1401		3.1
	1.25	SMKE1400	SMKE1401		3.5