Strengthening of a City Center Tunnel with Concrete Screw Anchors under Special Boundary Conditions

Johannes LECHNER
Dr.
Prof. Feix Ingenieure GmbH
Munich, Germany
johannes.lechner@feix-ing.de

Degree of Civil Engineering at the University of Innsbruck. PhD also at the University of Innsbruck in the field of shear strengthening.

Jürgen FEIX
Prof. Dr.-Ing.
University of Innsbruck and Prof. Feix Ingenieure GmbH
Innsbruck, Austria
juergen.feix@uibk.ac.at

Degree of Civil Engineering and PhD at TU Munich. Since 2003 chair for concrete structures and bridge design at the University of Innsbruck. Consultant and accredited checking engineer.

Robert HERTLE
Prof. Dr.-Ing.
Hertle Ingenieure and Technical University of Munich
Gräfelfing, Germany
robert.hertle@hertle-ingenieure.de

Consultant and design review engineer. Professor at Technical University of Munich and member of the board of the German Association of Design Review Engineers – BVPI –

Contact: johannes.lechner@feix-ing.de

1 Abstract

The Altstadtring-Tunnel is one of the essential east-west traffic routes in the city center of Munich and was constructed in the late 1960s. Segment 34 of the tunnel was built directly underneath the existing Prince-Carl-Palais, a historic building from 1804. Therefore 15 pre-stressed concrete girders with an effective depth of 3.5 m and a maximum span of up to 30 m were built which now form the tunnel roof slab. These girders were pre-stressed with steel nowadays well known for stress corrosion cracking. A recalculation of the slab showed that no ductile failure can be guaranteed in case of a progressive rupture of the tendons. Therefore, a concept for strengthening the slab was developed using concrete screw anchors as post installed bending and shear reinforcement. The concrete screw anchors are normally installed as anchoring elements in cracked and non-cracked concrete and are available with diameters up to 22 mm. Developing this concept further, it is straight forward to use these anchoring elements as post-installed reinforcement in existing concrete structures. This new strengthening system was developed at the University of Innsbruck in the last few years and can fulfill the special requirements of this project, such as installation of the strengthening system from underneath the tunnel slab during ongoing use of the structure. High strength steel with diameters of up to 63.5 mm will be used as post-installed bending reinforcement covered with a new shotcrete layer on the underside of the tunnel slab. In total 59.3 tons of new flexural reinforcement and 7199 concrete screws for strengthening the shear capacity of the girders will be used to ensure a ductile failure of the tunnel slab. The on-site work started in March 2019 and is expected to take two years to complete.

Keywords: strengthening of concrete structures, post-installed bending reinforcement, post-installed shear reinforcement, concrete screw anchors

2 Introduction

Most of the existing infrastructure in Central Europe was erected in the late 1960s up to the early 1980s, thus now being between 30 and 50 years old. This is valid not only for the age of concrete bridges, as shown in [1], but also for other infrastructure structures such as tunnels.

Since the erection of these structures the basis for the structural design has changed significantly. In particular the design against shear failure in the European standards has become more restrictive in the last decades, as different publications [2], [3] show.

Therefore, in recent years in-depth research has been done to develop new and more realistic design models to describe the shear ultimate limite state, such as detailed in references [4]-[8]. Especially the application of the structural models proposed in [7] and [8] result in the determination of a more accurate and hence significantly higher shear-resistance of the structure´s critical cross-sections. As these models depend in essence on the cross-section´s stress distribution, significant advantages are confined to pre-stressed structures. On the other hand, there is also a need for new, post-installed strengthening systems especially for structures such as concrete slabs. Hence, at the University of Innsbruck a new strengthening system was developed with special attention paid to fast installation and robust load bearing characteristics.

3 Concrete Screw Anchors as Post-Installed Reinforcement

3.1 General

The new idea is to use concrete screw anchors with nominal diameters of 16 mm and 22 mm as post-installed reinforcement for concrete structures. These easy installable anchors can fulfill the requirements of an efficient strengthening system, such as installation during ongoing use, installation from only one side of the structure and robust load bearing characteristics.

To prove the suitability of this new idea 63 shear tests with screw anchors as post-installed shear reinforcement and 21 punching shear tests with concrete screws as post-installed punching reinforcement have been performed at the University of Innsbruck's Unit of Concrete Structures and Bridge Design under the leadership of Prof. Feix.

3.2 Concrete Screw Anchors

Concrete screw anchors have gained in significant importance as anchoring elements in concrete structures since they were put on the market in the early 1990s. With growing demand, anchors with diameters of $d_0 = 16$ mm and $d_0 = 22$ mm were developed to obtain higher anchor loads and to have a wider field of application. These screws are installed with an additional adhesive to obtain higher anchor loads and a stiffer anchor behavior.

Concrete screw anchors are installed into predrilled holes with a defined diameter. Figure 1 shows a screw with a nominal diameter of $d_0 = 22$ mm. It can be seen, that the lower part of the screw is provided with a special thread which is larger in diameter than the nominal diameter. During installation this thread cuts itself into the concrete surface of the borehole (here 22 mm) which was made by hammer-drilling.

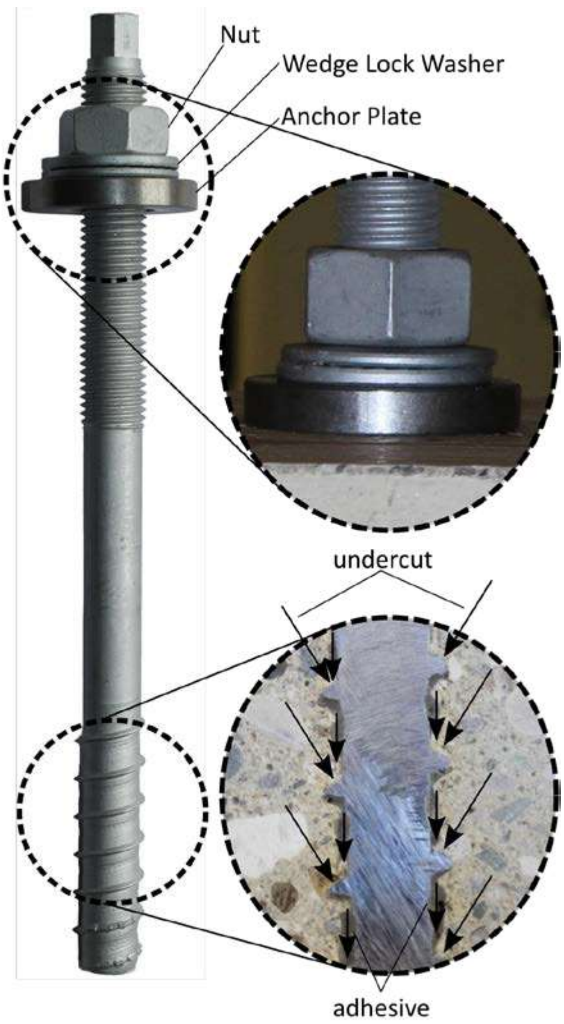


Figure 1. Adhesive Concrete Screw Anchors with load transfer mechanism and bracing

In Figure 1 it can also be seen that this cutting thread generates a mechanical load transfer to the concrete due to undercut. This develops a very robust and resistant load-carrying action compensating for irregularities during installation such as insufficiently uncleaned drill holes.

In Figure 1 the additional adhesive applied to the borehole is also shown (dark colored). This generates an additional load carrying capacity. Also the interlocking surface is enlarged by the resin.

This type of screw can carry loads of up to 200 kN using a glued installation procedure and concrete with a mean compressive strength of $f_{cm.cube} \geq 40$ N/mm². For this case the breaking strength of the steel is reached when a pull-out test with close supports is performed (see [9]). These tests had an installation depth of 17 cm in unreinforced concrete members. The same tests showed failure loads of up to 120 kN without the use of adhesive.

All of these screws are available with a special zinc-flake coating which guarantees a corrosion resistance of class C5 high according to DIN EN ISO 12944-6. For example, this is also the class demanded by the German codes for the use of steel elements affected by de-icing salt spray on bridges.

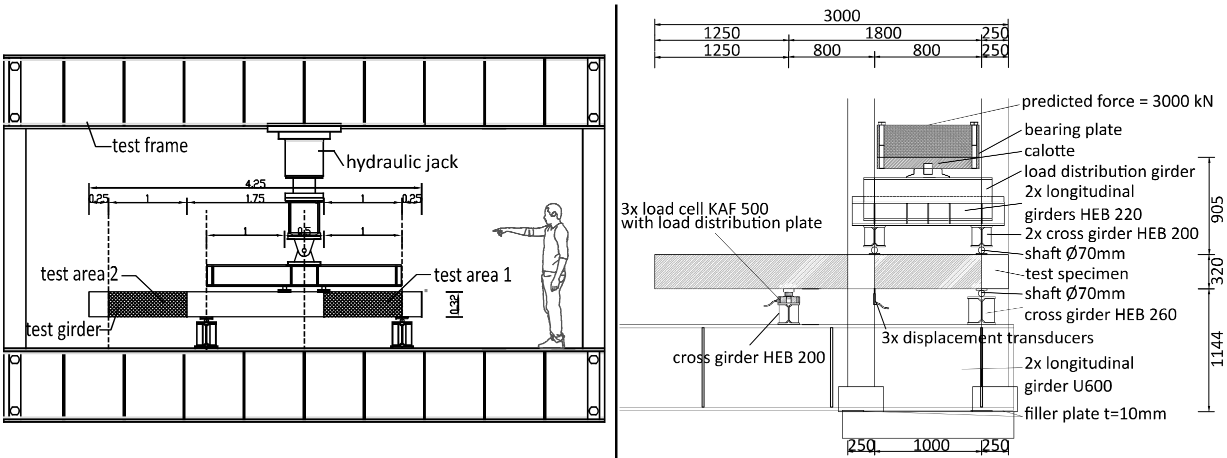
3.3 Shear Tests with Concrete Screw Anchors as Post-Installed Reinforcement

3.3.1 General

As concrete screws can fulfill the requirements for an efficient strengthening system, three series of tests with concrete screws as post-installed shear reinforcement were performed at the University of Innsbruck. The test beams contained only bending reinforcement. No shear reinforcement in the form of links or stirrups was provided.

The aim of these 32 tests was to prove the serviceability and strengthening effect of the new system. Therefore, several different parameters were investigated such as the installation of the screws with or without adhesive, different diameters ($d_0 = 22$ mm and $d_0 = 16$ mm) of the screws and different geometrical arrangements. An increase of the shear failure load of up to 124 % was observed compared to the reference tests without shear reinforcement (see [10]).

Three tests out of the first three test series were done with a dynamic loading pattern of up to 5 million load-cycles. The cyclic load applied was chosen between one third and two thirds of the approximated failure load, which means 70 kN and 140 kN. Two of the three tests were performed with screws of $d_0 = 22$ mm diameter – one without adhesive and the other installed with adhesive; the third test was made with 16 mm diameter screws installed with adhesive. All of these three tests showed no failure during the cyclic loading and they showed failure loads above the level determined in static loading tests. This results from a higher stiffness of the test specimen after the dynamic loading. More details about the dynamically loaded tests can be found in [11].



a) test setup for beam tests

b) test setup for slab tests

Figure 2. Test setup for beam tests at the University of Innsbruck and for slab tests at the University of the German Federal Armed Forces Munich

3.3.2 Tests for the Technical Approval

In 2018 an application for a national technical approval by the technical authority (Deutsches Institut für Bautechnik – DIBt) for the new system was made. To achieve the technical approval 31 additional tests were carried out in the fall of 2018 to provide more detailed results for additional parameters such as the installation depth. Therefore, tests on girders with heights of 320 mm and 440 mm were made at the University of Innsbruck with concrete screws of d_0 = 22 mm and d_0 = 16 mm in diameter.

Further tests of concrete slabs with a height of 320 mm and a width of 880 mm were made at the University of the German Federal Armed Forces in Munich with a hydraulic testing machine which can generate compression forces up to 10 MN. Figure 2 shows the test setup for the beam tests and also for the slab tests. Again, all specimens contained only bending reinforcement and were designed to allow for two separate shear tests on both ends of the girders or slabs respectively.

3.3.3 Test Results

The first tests were carried out with concrete beams with a depth of 320 mm and a width of 220 mm. The length of the shear field was 1 m which means a shear span of a/d = 3.45. For this test arrangement the two different screw diameters were analyzed in seven tests. Also two reference tests without shear reinforcement were carried out.

Tests with beams with a total depth of 440 mm but the same width of 220 mm were also carried out. The length of the shear field was also set at 1 m. This leads to a shear span of a/d = 2.44. In total eight tests were made with post-installed shear reinforcement of different diameter. Also the installation depth d_s was varied in such a way, that the top of the screw was installed under the upper flexural reinforcement.

Figure 3 shows the results of the beam tests. It can be seen that all reinforced tests had significant higher failure loads compared to the unreinforced reference tests. In detail, for the beams with a depth of 320 mm the load increase was 88 % for the tests with three 22 mm-screws (shear reinforcement ratio ρ_{sw} = 0.45%). With the same number of screws but with a diameter of 16 mm the measured load increase was 83 % with a shear reinforcement ratio of ρ_{sw} = 0.29%.

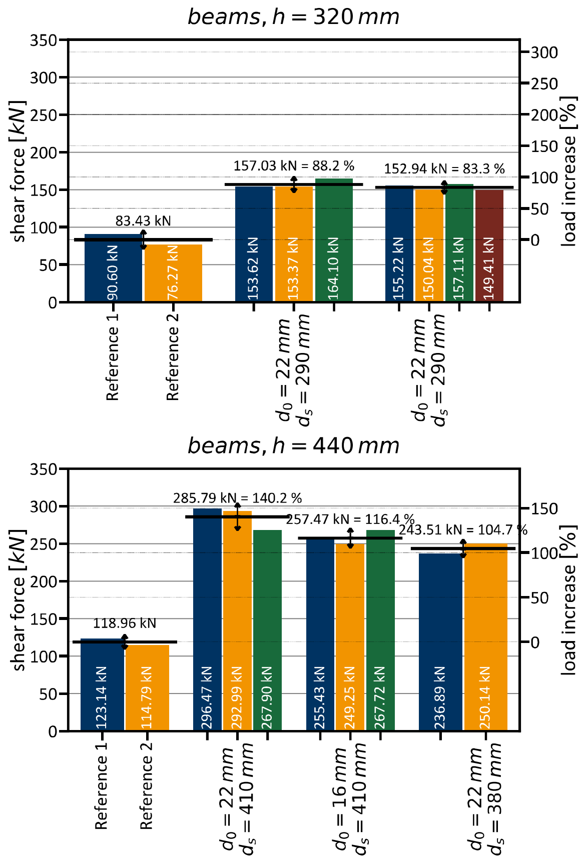


Figure 3. Failure loads of tests with concrete beams with two different heights and screws with variable diameter and installation depth

The achieved load increases of the tests carried out using beams with a height of 440 mm are shown in the lower graph of Figure 3. In these tests the influence of the shear reinforcement ratio to the possible load increase compared to the reference tests is more significant than for the tests with a beam height of 32 cm. Also, it can be seen that the installation depth of the screws has a significant influence on the failure load. Whereas the tests were the screw head is located above the flexural reinforcement showed a load increase of 140 %, the tests with an installation of the screws head underneath the flexural reinforcement showed a load increase of 105 %.

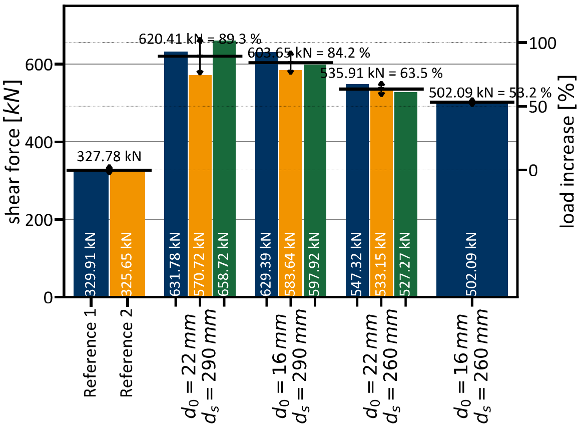


Figure 4. Failure loads of tests with concrete slabs and screws with variable diameter and installation depth

The comparison of the tests with beams of 320 mm and 440 mm depth respectively shows that the strengthening is more efficient the higher the beam. This results from an improved load transfer into the concrete compression zone. With the identical bond length of the screw (100 mm for the screw with a diameter of 22 mm) the anchorage of the screws reaches deeper into the compression zone and hence is more effective.

Figure 4 shows the test results of the shear tests on the concrete slabs with a depth of 320 mm and a width of 880 mm. Again, two reference tests without shear reinforcement were performed to derive the possible load increase. All tests showed a significant load increase of up to 89 % in good agreement with the tests performed on the beams. Again, these tests also confirmed the influence of the installation depth of the post-installed reinforcement.

The test results confirmed that a significant load increase can be achieved by applying the reinforcement method explained. Therefore, and also due to the fast and easy installation procedure, concrete screw anchors are highly suitable for application in structural strengthening projects with special boundary conditions such as the Altstadtring-Tunnel in Munich.

a) underpinning of the palais with steel beams

b) construction of prestressed concrete girders

c) excavation for building the tunnel walls

d) final excavation of the tunnel crosssection

Figure 5. Construction of segment 34 of the Altstadtring-Tunnel in Munich in the late 1960s, photos by the Building Department of the City of Munich

4 Strengthening of the Altstadtring-Tunnel, Munich

4.1 General

The Altstadtring is the central ring road in Munich and surrounds the city center of Munich. One key element of this ring road is the Altstadtring-Tunnel in the north of the city center with a total length of 610 m which is used by some 60,000 cars a day. This tunnel has maximum of three lanes in each direction. As there is no center-wall between the two directions the maximum span of the tunnel slab is 30 m in tunnel segment 34 which is to be dealt with in this paper.

The tunnel was planned and constructed in the late 1960s and was opened for traffic just before the Munich Olympic Games in 1972. Segment 34 of the tunnel, which is located under the historic Prinz-Carl-Palais from 1804 was built in a special type of cut and cover method.

4.2 Construction of Segment 34

As shown in Figure 5 the segment 34 was constructed under the Prinz-Carl-Palais. The first step was the underpinning of the building with steel beams in the basement level. Afterwards the basement was replaced by 15 concrete girders with a height of 3.5 m which were post-tensioned in a longitudinal direction. These 15 girders contain hollow voids to reduce the self-weight of the beams and were pre-stressed in the transverse direction to form the tunnel roof slab of segment 34. The complete load of the Prinz-Carl-Palais is now carried by these 15 girders. The walls were concreted afterwards and finally the cross section of the tunnel was excavated.

4.3 Results of the Recalculation and Initial Considerations

Because of the high number of tendons in both directions of the tunnel slab, the amount of conventional reinforcement is very low. Pre-stressing steel type Sigma Oval steel St145/160 was used in the construction. This steel is nowadays known for its tendency for stress corrosion cracking (see [12]).

In 2013 a recalculation was done on basis of the German assessment rules for structures containing tendons known to be susceptible to stress corrosion cracking. The conclusion of this analysis was that for 13 out of the 15 girders a ductile failure cannot be guaranteed. Therefore, and because of the permanent load of the Prinz-Carl-Palais the authorities decided to strengthen the segment 34 of the tunnel.

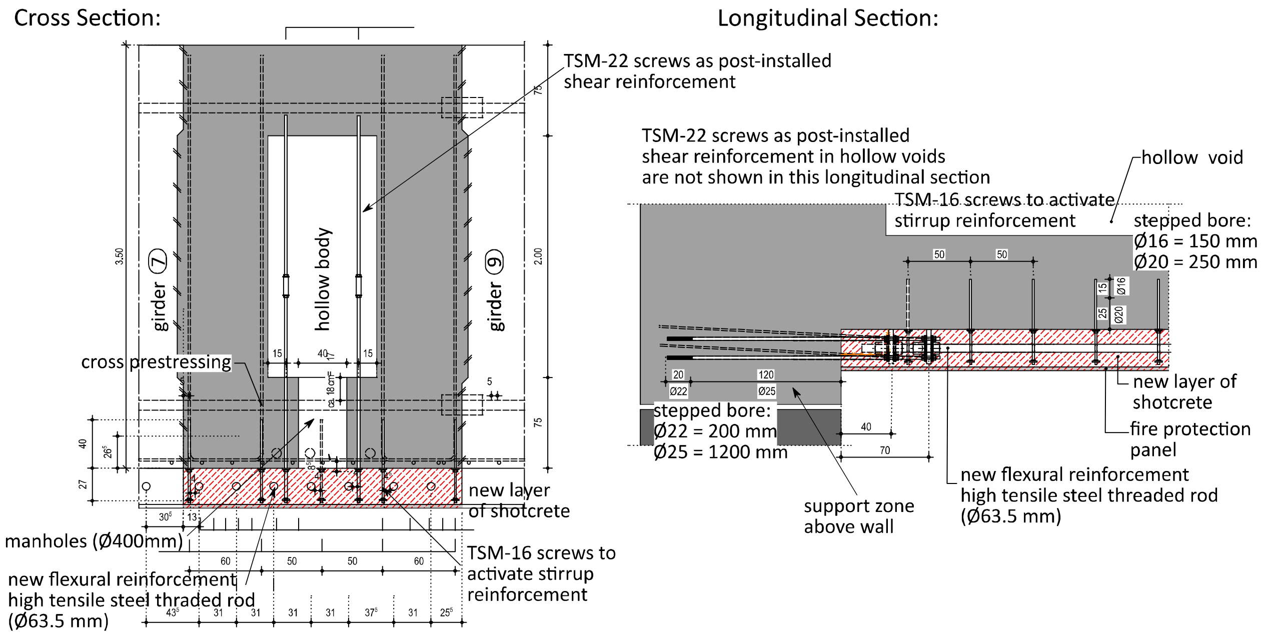


Figure 6. Planned strengthening system of segment 34 with concrete screws as post-installed shear reinforcement and threaded rods of high strength steel as bending reinforcement in a new shotcrete layer

In a first step, different types of strengthening methods were investigated such as post-installed tendons and CFRP laminates. Due to the limited installation options (no access from the upper side of the structure, installation under ongoing use of the tunnel) these options have been rejected. Using concrete screw anchors opens up the possibility that at least two lanes of the tunnel are available for traffic during installation and the installation can be done only from the underside of the tunnel slab.

4.4 Strengthening System

4.4.1 General

As Figure 6 shows, the proposed strengthening involves the installation of concrete screws with a total length of 3.2 m through the existing voids in the tunnel ceiling. These screws will be installed in the areas with a lack of shear reinforcement, next to the walls on both sides of the tunnel (see Figure 7). To get access to the 2 m high and 0.6 m wide hollow sections, manholes with a diameter of 400 mm will be drilled from the underside of the slab.

Concrete screws with a diameter of 16 mm and a length of 650 mm will be installed on the underside of the tunnel slab (1236 m²) in a grid of 500 mm by 500 mm to activate the existing stirrup reinforcement and to structurally connect the new shotcrete layer to the existing structure. Figure 7 shows the plan view of segment 34 with the 15 concrete girders which form the tunnel slab. Also the areas of different shear reinforcement strengthening can be seen.

As additional flexural reinforcement of threaded rods of high strength steel (f_{yk} = 670 N/mm², f_{tk} = 800 N/mm²) with diameters of 43 mm and 63.5 mm will be installed in a new layer of shotcrete (see Figure 6). These rods are anchored with two or four concrete screw anchors per bar on both sides of the tunnel into the support zone above the bearings (see Figure 6). As the threaded rods can be installed in individual lengths and can be connected by sleeve sockets / couplers, the installation can be made without a total closure of the tunnel.

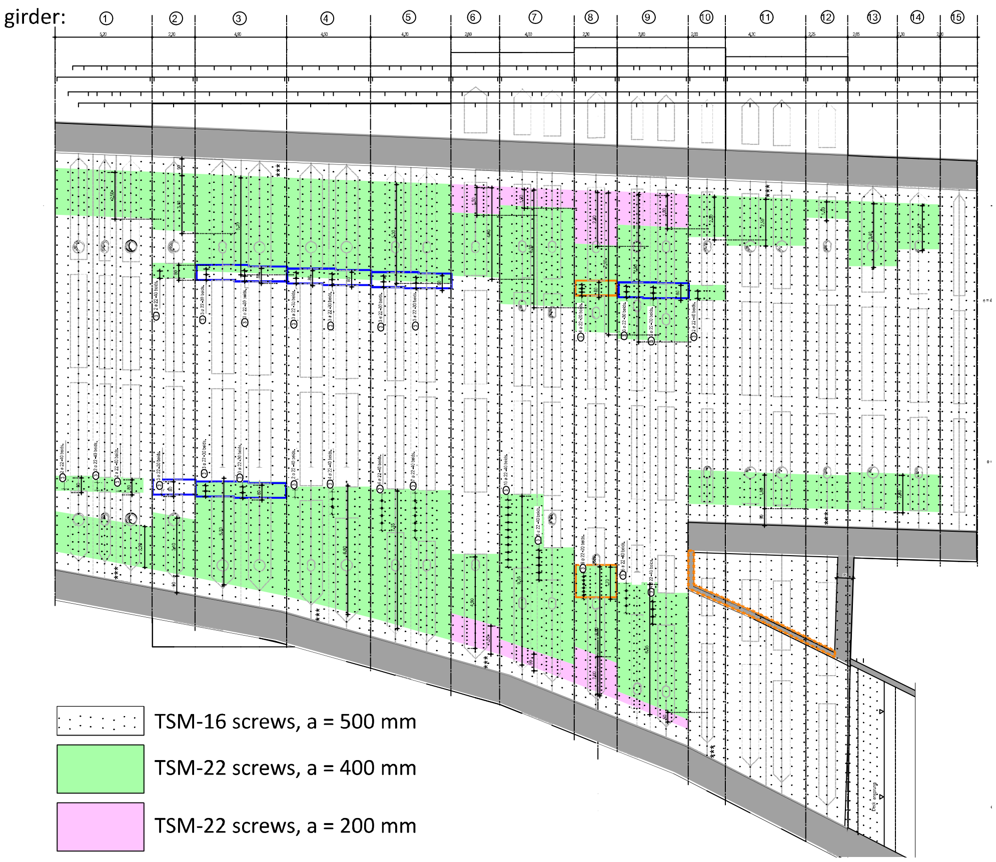


Figure 7. Plan view of section 34 with south exit and different areas shear strengthening

4.4.2 Preliminary Works

To prove the suitability of the proposed concept, preliminary works took place in April 2018. In total eight manholes were made and ten screws were installed through the hollow voids, as can be seen in Figure 8.

In four night closures of the entire tunnel eight manholes were made and in total twelve concrete screws were installed. As a first step the existing pre-stressing steel was located with a rebar detector and the position was marked on the ceiling.

Figure 8. Installation and installed screw anchors during the preliminary works

After drilling the manholes, the remaining formwork in the voids had to be cut in to pieces and was removed. The drilling was done completely from the underside of the slab. Therefore, workers had to access the voids only to position the drills into the upper flange. This enabled the work periods in the voids to be reduced to a minimum. The installation of the concrete screws was possible without any further restrictions.

4.5 Further Procedure

In autumn 2018 the works were issued for tender. At the beginning of this year the contract to carry out the works was signed and work started in March 2019. As there are several other improvement works to be done in the tunnel (such as the construction of a center-wall), the first step will be the marking of the tendons in longitudinal and transverse direction in segment 34. The next step will be the drilling of the necessary manholes and the installation of the concrete screw anchors.

The whole strengthening works of segment 34 are estimated to be carried out in 500 working days. In total 4954 screws with diameter 16 mm will be installed to activate the existing stirrup reinforcement. 1207 screws with diameter 22 mm will be installed as post-installed shear reinforcement. Additionally, 1038 screws with diameter 22 mm will be installed into the support zone above the bearings to anchor the 59.2 tons of new flexural reinforcement consisting of threaded rods made of high strength steel. 370 m³ of shotcrete will form the new underside of the tunnel slab.

The recalculation of the tunnel structure has shown that the load-bearing capacity of the tunnel slab as a pre-stressed concrete structure is sufficient, even if the actual valid verification formats are applied. However, as already mentioned, according to the results of the recalculation of the tunnel slab, should a fracture occur, this will most likely be a brittle fracture. This is due to the stress-corrosion of the pre-stressing steel. The reinforcing measures which are being carried out, will in the event of the rupture of the pre-stressing tendons, ensure a ductile failure with early warning due to visible crack patterns on the surface of the tunnel slab.

5 Conclusions

Due to the existing constraints, a method had to be found for the strengthening of segment 34 of Munich´s Altstadtring-Tunnel which, on the one hand, could be installed during ongoing use of the tunnel and, on the other hand, guaranteed a simple and fast installation as well as a robust load-bearing behavior.

Based on the shear tests carried out at the University of Innsbruck and on the experience already gained with the recently developed concrete screws as post-installed reinforcement in pilot projects (see [13]), a reinforcement concept based on concrete screws was developed for the tunnel roof slab. The preliminary works already carried out showed the feasibility of the proposed measures. At the same time, it became obvious that for the successful implementation of the proposed measures a detailed planning in advance is crucial. Therefore, not only the final design documents but also the tender documents had to have a very high level of detail concerning the new reinforcing elements with respect to the location of existing elements such as the longitudinal and transverse tendons.

However, for a project of this size it is likely that many unforeseen difficulties will occur within the next two years which can only be mastered by constant contact between the design office, the contractor and the tunnel owner.

6 Acknowledgements

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The authors also want to thank the employees of the building department of the City of Munich for their cooperation and for the opportunity of using the new system for this challenging project.

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