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ENHANCED SERVICE LIFE OF EXISTING INFRASTRUCTURE BUILDINGS BY USE OF CONCRETE SCREW ANCHORS AS POST-INSTALLED SHEAR REINFORCEMENT

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Abstract. In the last decades, traffic on railways and roads has increased significantly in Central Europe. On the other hand, the existing infrastructure mainly origins from the late 1950s to the 1970s. This applies also for the existing bridge and tunnel infrastructure which is now up to 60 years old. Due to this age and new standards in the current codes, quite often the amount of shear reinforcement does not fulfil the current design code rules. As a replacement of existing structures is often highly unsustainable, methods to improve the shear strength are needed. Therefore, a new system for post-installed shear reinforcement by the use of concrete screws was developed at the University of Innsbruck in the last years. The idea is to use concrete screw anchors - already known as anchoring element - as post-installed reinforcement. In over 60 shear tests with girders and slabs the excellent applicability of concrete screw anchors as post-installed shear reinforcement has been proven. Also shear tests with cyclic loading were performed prove the use for dynamically loaded structures, such as bridges. Based on these test results a design approach was determined to meet the Eurocode-2 assessment standards.Several pilot-projects with concrete screws have been realised in Austria and Germany. For example a rail-road-bridge over a German highway with a remaining service life of zero years was strengthened to a new service life of over 20 years. Also a city-centre tunnel in Munich which was erected below a historic building is currently strengthened under ongoing traffic in the tunnel using concrete screw anchors as post-installed reinforcement.

Keywords: Bridge strengthening, concrete screw anchors, shear strengthening.

1. Introduction

Most of the existing infrastructure in Central Europe was erected between the late 1960s and the early 1980s. According to [1] nearly 60 % of the German bridges date from the decades between 1960 and 1990 and therefore are now between 30 and 60 years old. This applies not only to Germany but also to nearly all countries of Central Europe, where most of the railroad and road infrastructure was built after World War II.

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.

Several different investigations [4–6] show the economic impact on the reliability of the transportation network of the developed countries. While factors such as in-time production are becoming more and more important, the reliability of the transport infrastructure is decreasing with growing age. At the same time, evasion traffic and congested traffic routes represent a significant burden on the environment. For this reason, disruption of traffic for maintenance measures or the replacement of structures should be avoided or kept as short as possible. A significant contribution to the avoidance of such closures can be made by keeping existing infrastructure in service.

Therefore, in recent years a lot of research has been put into developing new and more realistic design models at the shear ultimate limit state, such as detailed in references [7–9]. On the other hand, there is also a need for new, post-installed strengthening systems to keep existing infrastructure in service. Hence, at the University of Innsbruck a new strengthening system was developed with special attention paid to fast installation and robust load bearing characteristics.

2. Concrete Screw Anchors

2.1. General

The new idea is to use concrete screw anchors with nominal diameters of $d_0 = 16$ mm and $d_0 = 22$ mm as post-installed reinforcement for concrete structures. These easily installable anchors can fulfil 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.

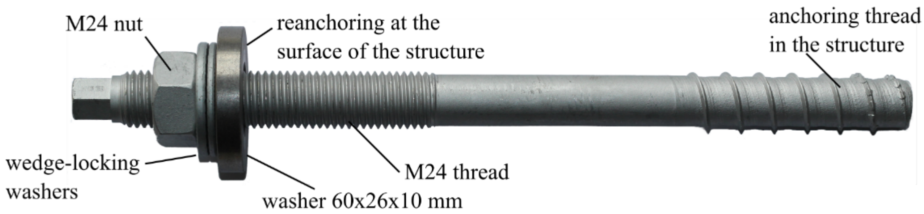

Figure 1. Concrete Screw Anchor with anchoring thread which creates a form-locked connection and the re-anchoring at the concrete surface of the structure.

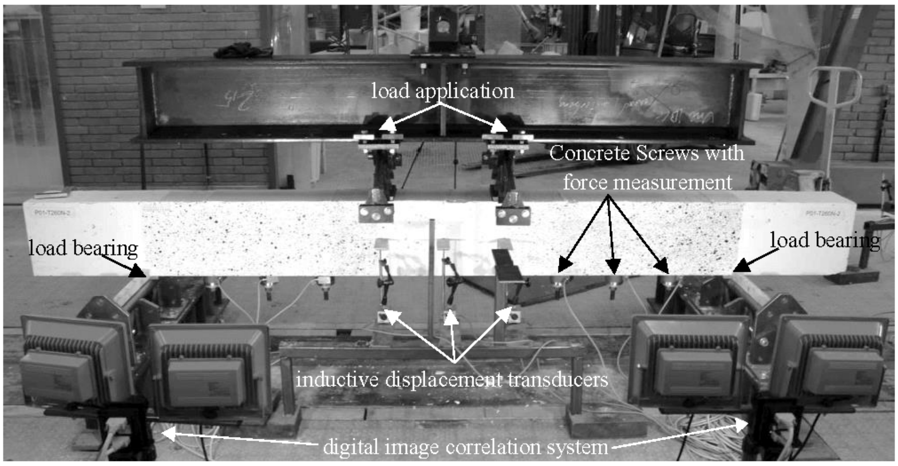

Figure 2. Test setup and measuring systems of the shear tests with concrete screw anchors at the University of Innsbruck.

To prove the suitability of this new idea, 67 shear tests in total with screw anchors as post-installed shear reinforcement have been performed at the University of Innsbruck's Unit of Concrete Structures and Bridge Design.

2.2. Concrete Screw Anchors

Concrete screw anchors are known as anchoring elements with easy installation in concrete structures and are more frequently used nowadays. With growing demand, anchors with diameters of 16 mm and 22 mm were developed to anchor higher loads and to achieve a wider field of application such as the anchoring of poles of noise barrier walls on bridges. Therefore these screws are installed with an additional adhesive to obtain higher anchor loads and stiffer anchor behaviour. These screws have a technical approval by the German railroad authorities for the use under dynamic loading up to 5 mio. load-cycles, for example for the use as anchor for noise-barrier walls near railroad traffic.

Concrete screw anchors are installed into predrilled holes with a defined diameter. Figure 1 shows a screw with a nominal diameter of $d_0 = 22\,\text{mm}$. It can be seen that the first part of the screw is provided with a special thread which is larger in diameter than the nominal diameter of the drilled hole. Therefore, during installation this thread cuts itself into the concrete surface of the borehole which can be made by hammer-drilling or core-drilling. A mechanical load transfer is thus generated on basis of undercut. This develops a very robust and resistant load-carrying action compensating for irregularities during installation such as insufficiently uncleaned drill holes.

The type of screw shown in Figure 1 can carry loads of up to 200 kN using a glued installation procedure and concrete with a mean compressive strength of $f_{cm.cube} \geq 40\ \text{N/mm}^2$. For this case the breaking strength of the steel is reached when a pull-out test with close supports is performed (see [10]). The same tests showed failure loads of up to 120 kN without the use of adhesive.

2.3. Concrete Screw Anchors for the use as post-installed reinforcement

For the use as post-installed shear reinforcement the screws have been slightly modified. Also re-anchoring elements have been developed as can be seen in Figure 1. These elements re-anchor the acting axial forces in the concrete screw on the surface of the structure with a large washer, a wedge-locking washer to avoid loosening of the standardised nut during cyclic loading. As the concrete screw anchor is equipped with a standardised thread (e.g. M24 in Figure 1) the re-anchoring can be adjusted to the necessary length and a prestressing force can be applied easily by turning the nut.

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

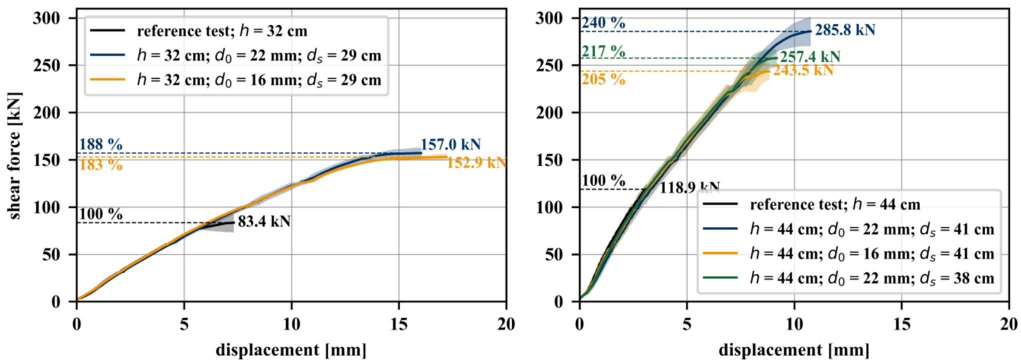

Figure 3. Test results of concrete test girders with heights of 320 mm and 440 mm and with concrete screws of different diameters d_0 (22 mm and 16 mm) and different installation depth d_s.

German codes for the use of steel elements affected by de-icing salt spray on bridges.

Concrete screw anchors as post installed shear reinforcement have many advantages compared to other shear reinforcement systems such as the easy installation from the underside of the bridge without disruption of the ongoing use of the bridge and the mechanical load transfer.

3. Experimental research at the University of Innsbruck

3.1. First tests at the University of Innsbruck

To show the usability and enhancements of the new method, several test series with in total 67 single tests at concrete girders and slabs have been performed.

Between 2013 and 2016 32 shear tests in 3 test series at concrete beams have been performed. The tests were made as four-point-bending tests as can be seen in Figure 2. These tests were equipped with concrete screw anchors of different diameters d_0 (22 mm and 16 mm) and carried out in different geometrical arrangements using glued and non-glued installation to proof the applicability of the new system. The method was experimentally analysed with concrete beams of 3.5 m in length. In several different variations of screw diameters and installation geometry all tests resulted in a remarkable increase in shear load capacity of up to 120 % using glued installation. Also in un-glued installation a remarkably load increase was determined. In the third test series the influence of the installation depth ds was investigated. The results showed an influence on the maximum load when the anchoring end of the screws was located at the upper side of the upper flexural reinforcement and the end of the screws was located under the upper flexural reinforcement respectively. More detailed information on the relevant test results can be found in [11], a summary of the basic outcome can be found in [12].

Three tests were made with dynamic loads of 1.25 million and 5 million load cycles between 70 and 140 kN with 2 Hz. This means a dynamic load of between 1/3 and 2/3 of the failure load of the statically loaded comparative test. In comparison, all three tests showed no failure during the dynamic loading and even higher failure loads at static loading afterwards compared to the comparative tests. The results showed that this system achieves a significant increase in shear strength of concrete structures under dynamic load conditions such as bridges in a very robust and economically efficient way (see [12–14]).

3.2. Tests for the technical approval

An application for a national technical approval by Deutsches Institut für Bautechnik - DIBt - for the new system was made in 2018. Therefore, additional tests were performed in fall 2018 to achieve more detailed results for special parameters such as the installation depth d_s. Tests on girders with heights of 320 mm and 440 mm were made at the Laboratory of the University of Innsbruck with concrete screws of $d_0 = 22\,\text{mm}$ and $d_0 = 16\,\text{mm}$ in diameter. Furthermore, tests with concrete slabs with a height of 320 mm and a width of 880 mm were performed at the University of the German Armed Forces in Munich with a hydraulic testing machine generating testing forces up to 10 MN. To achieve information about the deviation of the failure loads, up to four tests for every configuration were carried out.

Figure 3 shows the test results of the beam tests with a height of 320 mm compared to the tests with a height of 440 mm. The span of all beams was 2.5 m, which means a variation of the shear span ratio a/d. It can be seen that at the beams with a height of 320 mm no influence of the screw diameter can be identified when using the same number of screws. The maximum shear force differs from 157 kN to 153 kN. This means a load increase of 88 % and 83 % compared to reference tests respectively.

The tests with a beam height of 440 mm were made with the same number of concrete screw anchors as the tests with a height of 320 mm. Figure 5 shows that these tests achieved load increases of up to 140 % compared to reference tests. This higher strengthening effect results from a better load transfer when

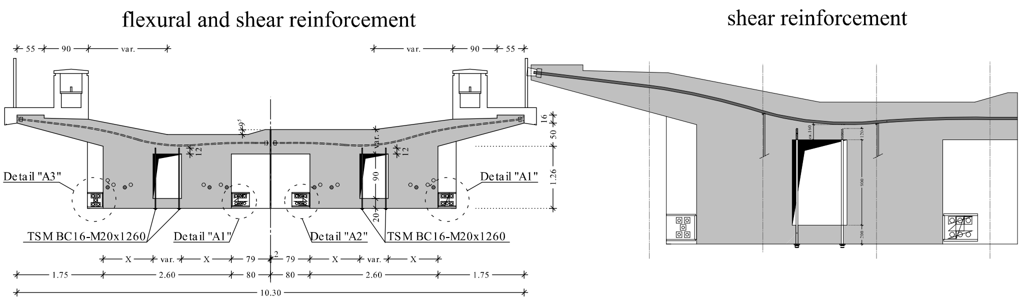

Figure 4. Additional flexural reinforcement on both sides of the hollow box girder and additional shear reinforcement drilled through the hollow box.

Figure 5. Strengthening of the railway bridge over the highway A70 under ongoing use on and under the structure.

anchoring higher into the flexural compression zone with the screws. While there was no significant difference between the $d_0 = 22$ mm and $d_0 = 16$ mm screws at the beams with a height of 320 mm, the tests with 440 mm show a difference in load increase of 23 %. Also, it can be seen that for these tests an influence of the anchoring depth d_s of screws is significant when anchoring under and at the same height as the upper flexural reinforcement.

Also tests at slab specimen were performed. For the concrete slabs the shear reinforcement ratio was identical to the beam tests. So the test results can be compared to them and are in good accordance with the performed beam tests. The variation of the installation depth also showed a reduced maximum shear force when using a reduced installation depth d_s in accordance to the beam tests.

3.3. Conclusion of the performed shear tests

All tests showed that with the use of the new system significant load increases can be achieved. Therefore and due to the fast and easy installation, the system is highly suitable for the application in strengthening projects with special boundary conditions such as installation under ongoing use. The tests showed that the new system can be used for the strengthening of existing structures also with dynamic loads such as bridges. Therefore this new system can contribute strongly in maintenance and strengthening of existing infrastructure and can contribute to avoid road closure due to replacement constructions or other complex strengthening systems.

4. Pilot-Projects

4.1. Railway Crossing over the German motorway A70

The railway crossing over the German motorway A70 near Bamberg is a two span concrete bridge which was built in 1967. The girder bridge has a maximum span of 17.5 m and two separate superstructures with a hollow box cross-section, as can be seen in Figure 4. The bridge is prestressed with tendons manufactured from Sigma Oval 40 (St 145/160) steel which is known for its tendency to stress corrosion.

A recalculation of this bridge was performed in 2011 revealing a remaining service life of zero years. Due to the possibility of a sudden failure through a rupture of tendons no ductile failure of the superstructure could be ensured. This is why a bending and shear strengthening was planned using concrete screw anchors. One requirement of this strengthening was the installation under ongoing traffic on the bridge.

To raise the shear load capacity concrete screw anchors with a length of about 125 cm from underneath the bridge were drilled through the hollow boxes. To increase the flexural bending failure load steel plates as external reinforcement were attached at both sides of the girder, as can be seen in Figure 4 and 5. These steel plates were prefabricated in small elements and fixed with concrete screw anchors to the structure.

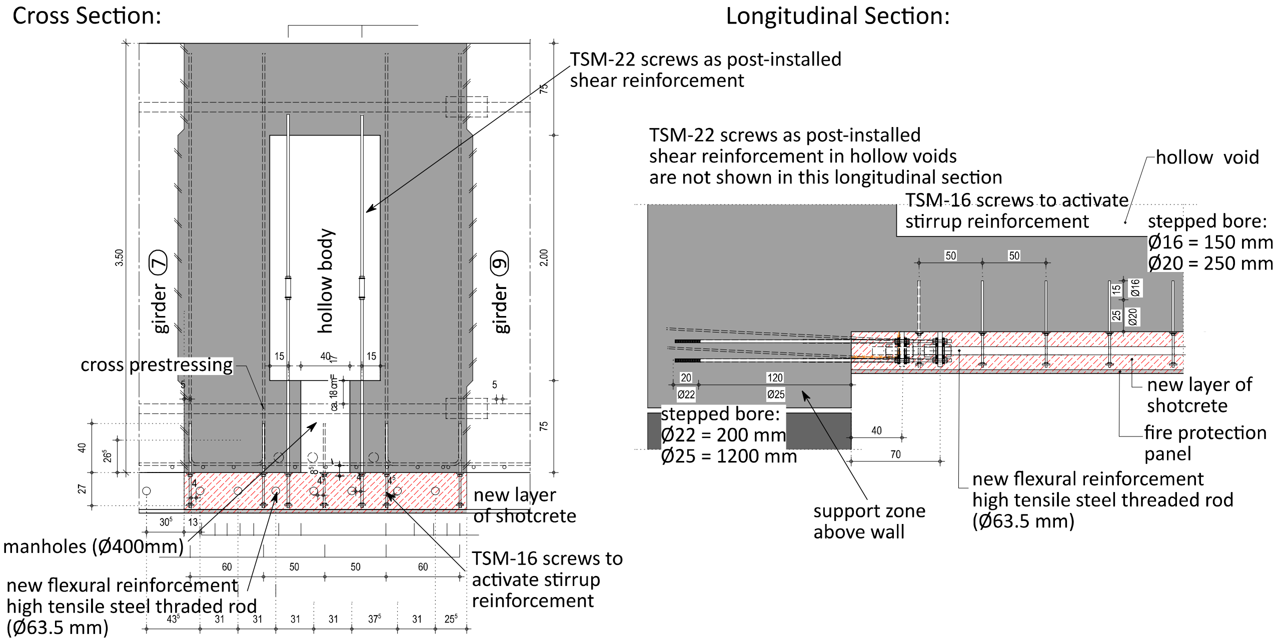

Figure 6. Planned shear and flexural reinforcement by the use of concrete screw anchors as shear reinforcement and threaded rods of high tensile steel as new flexural reinforcement.

This resulted in short delivery and assembly time. The short elements of the steel plates facilitated the closure of just single lanes for the installation. This led to a very small traffic disruption of the motorway as can be seen in Figure 5.

Especially at both ends of the bridge strong deficits of existing flexural reinforcement was given. Therefore the full force of the steel plates had to be anchored into the end cross girder. Six screws $d_0 = 22$ mm with a length of 2.3 m were used to transfer this load into the concrete.

The whole installation time of the reinforcing system was four weeks. The total cost was about €370 000 whereas a rebuilding of the structure was calculated with around 2.5 million Euros. Furthermore, no disruption of the railroad traffic was necessary.

4.2. Segment 34 of the Altstadtring Tunnel, Munich

The Altstadtring Tunnel in Munich is one of the main east-west traffic axes in the centre of Munich. The daily traffic through the tunnel is about 60 000 cars on four lanes. The tunnel was built at the end of the 1960s mostly in open type construction and was opened in 1972 for the Olympic Games in Munich. Some segments of the tunnel were erected by top-down construction method. One of these is segment 34, which was built underneath the Prinz-Carl-Palais. Therefore, the basements of the building were broken off and in total 15 girders with a height of 3.5 m were built section by section underneath the palais. Afterwards the tunnel cross section was excavated under the new slab. Therefore, the complete dead load of the Prinz-Carl-Palais is carried off by the tunnel slab.

The 15 girders which form the tunnel ceiling slab of segment 34 were designed as single span girders, with a maximum span of up to 35 m. The girders were built with a box cross section and prestressed with tendons. Again, pre-stressing steel type Sigma Oval steel St145/160 was used. Because of the high number of tendons in both directions of the tunnel slab, the amount of conventional reinforcement is very low. In 2013 a recalculation was executed on basis of the German assessment rules for structures containing prestressing steel known to be susceptible to stress corrosion cracking. It was concluded that for 13 out of the 15 girders a ductile failure cannot be guaranteed. Therefore, the authorities decided to strengthen segment 34 of the tunnel.

The planned reinforcement is a combination of concrete screw anchors to raise the shear load capacity and high tensile threaded rods as post-installed flexural reinforcement at the underside of the slab, as shown in figure 6 for one girder. The additional shear reinforcement is drilled through the hollow boxes near the supports. In total more than 1000 concrete screws with a length of 325 cm are needed as additional shear reinforcement.

The flexural reinforcement is planned with a diameter of 43 mm and 63.5 mm respectively. The additional external reinforcement will be cladded in a 30 cm layer of shotcrete. To ensure the correct bond between the existing concrete structure and the shotcrete and to activate the existing stirrup reinforcement, 5000 concrete screws with a diameter of 16 mm are therefore planned to be installed in the whole area of 1236 m^2. This is also shown in the right picture of Figure 6.

In spring 2019, the strengthening measures for the tunnel reinforcement were started, whereby in a first step the screws were installed on the north side of the tunnel. For this, traffic was rerouted, whereby at least two lanes had to remain open at all times. After a detailed non-destructive detection of the existing tendons, the manholes necessary for the installation of the screws could be produced into the hollow bodies. Afterwards the installation of the reinforcing screws could be started. The installation of the bolts in the northern half of the tunnel was completed in October 2019. In the next step, the high-strength threaded rods were installed on the underside of the slab and traffic was transferred to the north side so that work could continue on the south side of the slab.

The work on the south side is currently being carried out. After the installation of the remaining bolts (a total of approx. 7300 bolts), the new bending reinforcement will be mounted on the south side and connected to the reinforcement on the north side with joints. Finally, a shotcrete layer of 30 cm will be applied to the underside of the slab, thus restoring the level ceiling soffit.

5. Summary

A significant number of concrete structures lack of shear reinforcement. Therefore, several research projects aim to develop a new shear strengthening system to increase their shear strength. Such systems aim at easy installation without disruption of the use of the structure. The new idea presented in this paper is to use concrete screw anchors as post-installed shear reinforcement system.

In several pilot projects the easy and fast installation of the new retrofitting system was proved. A railroad bridge over the German motorway A70 was reinforced with concrete screw anchors as shear reinforcement and external flexural reinforcement within 4 weeks under ongoing traffic on and under the bridge. Thus it was possible to extend the life span of the bridge from zero to 20 years. Also the tunnel slab of the Altstadtring-Tunnel in Munich is currently reinforced by the use of concrete screw anchors. As this tunnel was erected under the historic Prinz-Carl-Palais and represents the central east-west route through the city of Munich, a total closure or replacement construction was not possible.

Summarising, it can be seen that the new system, the usage of concrete screw anchors as post-installed reinforcement can raise the load capacity of existing structures significantly. Because of the easy and fast installation of the system, it is very well-suited for the strengthening of structures under ongoing use. Using the new system, the lifetime of existing structures can be increased significantly and disruptions to traffic by road closures or rerouting can be avoided or reduced. In [15] it was shown, that strengthening of existing structures with minimal road-closures on and under the bridge reduces the impact on the global warming potential, the acidification and on non-renewable CEDs up to 200 % on one day compared to a replacement of the bridge. A new and quickly installable reinforcement system can help reduce emissions such as CO_2.

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