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Adopting hollow bar: lessons learned

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Abstract

Boliden strives to increase efficiency and quality, and to enable automation during bolting operations. To this effect, a trial with hollow bar rockbolts with pumpable resin as grouting was performed at the Renström mine. As part of this trial, tests were carried out to verify the capacities of the new bolt and determine the required anchor length needed.

In the initial testing during 2020 using a hollow bar from DSI Underground (DSI) with standard steel (R25, 22 t ultimate strength, 5% deformation capacity) results showed that the ultimate strength was good, and the anchor length was slightly longer than for a rebar bolt. The deformation capacity was, however, not sufficient.

For the 2022 trials, DSI supplied a bolt with modified steel characteristics (Ductile R25, 15% deformation capacity) that, in external lab tests, showed the desired deformation capacity together with the required strength of the grouting material. The first tests of the field trial failed to repeat these results and the expected anchor length was not achieved. A program of eliminating error sources and finding alternative solutions followed.

The trials revealed that several factors played a part in achieving the desired anchor length. A replacement for the current rebar bolt needed at least 500 mm of anchor length and therefore, hollow bar bolts of 2.9 m length were ordered for future use.

This paper summarises the investigations, changes and lessons learned in these trials, with respect to anchor lengths, curing time, impact of temperature and installation practices.

Keywords: *pumpable resin, hollow bar, short encapsulation, pull-out test*

1 Introduction

1.1 Background

Boliden strives to increase efficiency and quality while also enabling automation during bolting operations. Hollow bar bolts, together with pumpable resin, offer a potential way forward. By using the hollow bar bolt to fill the drillhole, complete encapsulation (grouting) is assured compared to the top-hole filling normally used with cement grouting. The pumpable resin is also less sensitive to installation errors due to bad mixing or oversized/fractured boreholes compared to grouting with resin cartridges. Together with the supplier DSI Underground (DSI), a trial was performed at the Renström mine in Sweden in 2022 with their hollow bar bolt and pumpable resin products to see if the method was more cost-efficient.

As part of this larger trial, the required anchor length of the hollow bar bolts had to be determined and thereby the total bolt length required to meet the demands of the reinforcement. These tests are the main subject of this paper.

The requirements for the bolts ahead of the trial was that they should match the performance of the current standard rebar bolt to avoid changes or mix-ups with existing reinforcement plans. The current standard bolt is a rebar grouted with either resin cartridges (styrene plastic) or cement. The capacity of the bolt is 20 t ultimate strength with a 15% deformation capacity over a single joint using a B500SP steel. Current bolts at Renström are 20 mm in diameter, 2.7 m long, they need a minimum of 300 mm anchor length in resin and have a deformation capacity of 30–40 mm over a single joint.

1.2 The Renström mine

The Renström mine is currently the deepest operating mine in Sweden with production between 500 and 1,500 m depth below surface. Development is ongoing for an access ramp towards 1,700 m depth for exploration purposes.

The Renström mine is situated in the northern Swedish county of Västerbotten, 50 km west of the city of Skellefteå and about 200 km south of the Arctic circle. From the mine it is 20 km by road to the concentrator in the town of Boliden. Boliden also operates two other underground mines in the area.

The rock conditions in the mine are complex with large variations, from strong volcanic intrusions in the host rock to soft, chloritic or fractured zones in and around some of the ore bodies. Most of the rock has a uniaxial compressive strength of 80–140 MPa. The stronger rock types reach over 200 MPa and the weakest zones are below 50 MPa. The rock has an RMR_{76} rating of 50–70 for most rock types except ones with a high degree of chlorite alteration.

The large depth, in combination with influence from mining, causes high stresses that result in deformations in the order of tens of centimetres depending on area and stand-up time.

The difference in rock temperature between the upper and lower parts of the mine is in the order of 10°C (about 1°C increase per 100 m depth).

1.3 Bolt installation procedure and definitions

The principal idea of hollow bar bolts is that grouting is done through the centre hole of the bolt. The two-component resin is mixed in the nozzle and injected through the bolt to the toe of the hole where it exits the hollow bar and flows back down the hole on the outside of the bar towards the collar leading to total encapsulation of the bar. This ensures a higher quality of grouting. Drilling can be performed either as usual with a standard, separate drill rod and bit (two-step method) or using the bolt itself as the drill rod with a sacrificial drill bit that is left grouted in place (one-step method). The one-step method permits bolt installation in very broken ground. The drill bit then also serves as an extra anchor for the bolt.

The two-step method was almost exclusively used for the trials described in this paper. With the equipment used in the trials, the installation sequence is as shown in Figure 1.

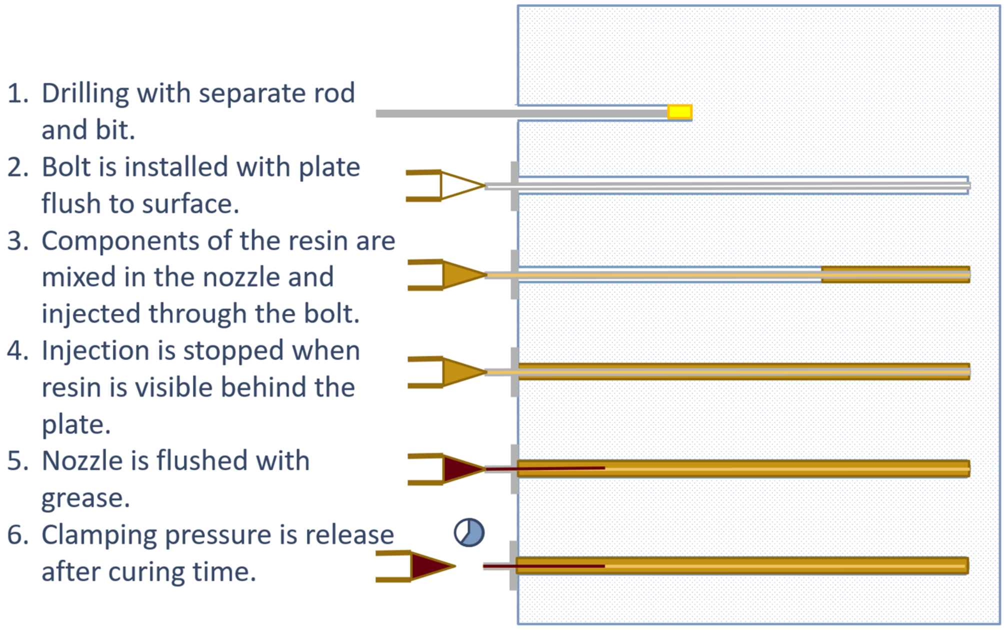


Figure 1 Installation procedure for two-step bolting with hollow bar

In this test, the objective was to determine the anchor length of the bolt and by extension, the total bolt length. The total length of the bolt, as shown in Figure 2, is the sum of:

- The required anchor length: the minimum grouted length necessary to use the full strength of the bolt.
- The effective/usable length of the bolt: determined by the largest load that can be carried by a bolt, usually for the purpose of block/wedge retention.
- The free/ungrouted bolt length: the length necessary for installation and face plate retention.

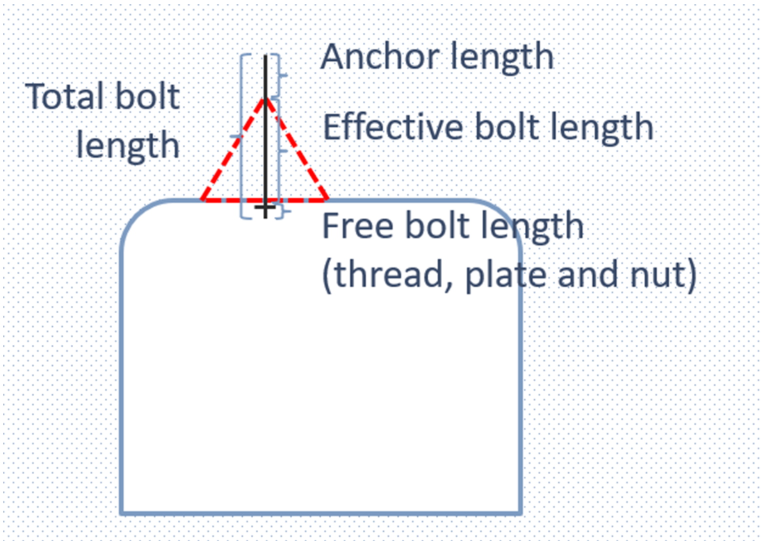


Figure 2 Definition of anchor length, effective bolt length and total length

2 Timeline of tests and investigations

2.1 Initial testing in 2020

An initial round of testing was conducted in October 2020 to choose the type of bolt and determine the required anchor length in preparation for the coming large-scale testing. The test was also carried out in varied rock conditions to determine if there were any obvious differences in behaviour for installations in competent or weak rock. Most of the tests were done on R25 hollow bars (25 mm outside diameter) with 11 bolts tested in total. Comparative tests were done with R22 hollow bar (22 mm outside diameter, four tests) and high-deformation capacity R28 bolts (28 mm outside diameter, two tests) where each bolt consisted of two sections of profiled anchors with smooth bar profile in between, similar to the D-bolt. The steel in all the bolts had a deformation capacity of 5%. The nominal ultimate strength for the bolts was 22 t for R25, 17 t for R22 and 26 t for R28.

The tested bolts (2.2 m long) were fully encapsulated with resin but were decoupled from the resin for testing the varying anchor lengths. The normal hollow bars were decoupled by a soft water hose placed over the thread of the bolt. The hose was soft enough to see the contours of the bolt through it. The high-deformation capacity bolt was decoupled by the smooth sections. Tested anchor lengths were 500 and 250 mm for R25; 500, 300 mm and 250 mm for R22; and 700 mm for R28. Only one test per bolt of the shortest anchor lengths were tested for R22 and R25 due to the available number of bolts.

One of each R25 and R22 was also fully grouted for torque strength testing (to simulate the installation and tightening of the nut).

The test was carried out after curing times ranging from one to 15 minutes.

Installation and grouting were done manually in pre-drilled bore holes using a self-contained unit for pumping and mixing the two-component resin. The two-component resin used was Mineral Bolt, also supplied by DSI. The pull-out tests were performed using a manually operated hydraulic jack with electronic logging of the results (see Figure 3.)

Iso-cyanate emissions in air was also measured during testing as a part of the trials.

Figure 3 Hydraulic jack and tripod used during testing

The tests in weak rock gave no clear results, partially because of the condition of the test site but also some initial issues with the installation equipment meant that fewer bolts than planned could be tested: two bolts were tested to failure after 12–15 minutes of curing time. One bolt was pulled out of the resin after two minutes. One bolt showed promising results, but the testing rig punched through the shotcrete and the results were therefore invalid.

The tests in the competent rock were much clearer: three of the R25 bolts reached over 20 t capacity, but one test was aborted after the support leg for the testing rig failed. The one R25 bolt with short encapsulation length (250 mm) reached 95% of the capacity of the steel before it was pulled out of the resin. The only bolt that did not show results near the ultimate failure strength was a bolt that was pulled after one minute of curing time (deliberately) with a result of 12 t.

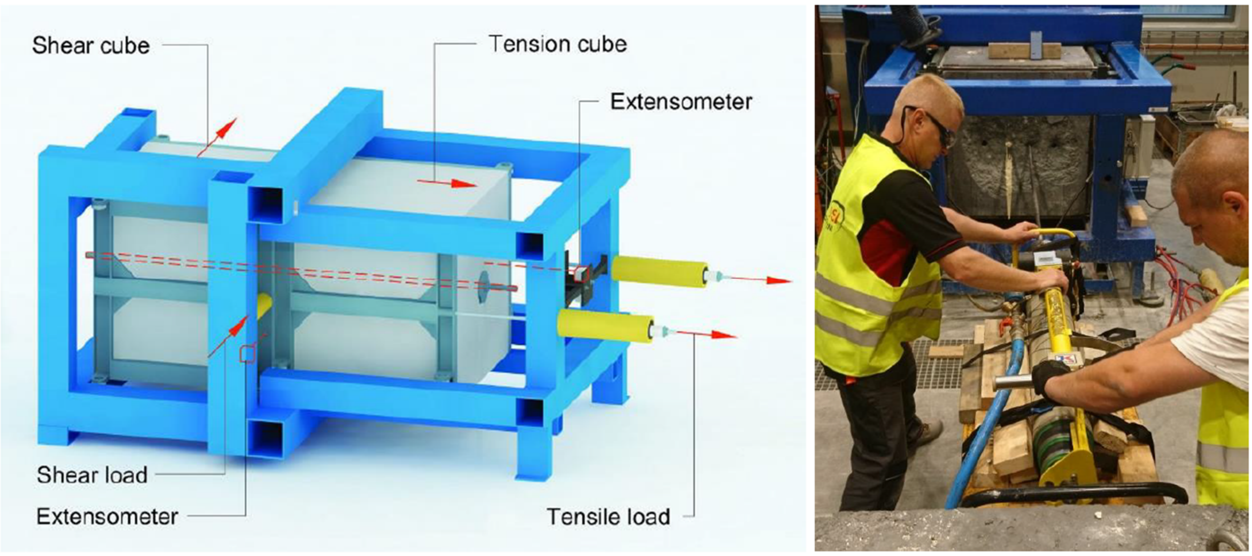
All tests for the R22 and R28 bolts were deemed successful. The R22 bolts reached 16 t yield strength at 500 and 300 mm anchor lengths after two and five minutes of curing, respectively. The R28 bolt started deforming at 21 t but was capable of over 20% deformation before failure.

Based on the results, it was assumed that an R25 bolt should be able to withstand 17–18 t of force after a few minutes with 300 mm of anchor length (about 57 t/m), which is in line with the currently used standard rebar, but that more tests were needed to confirm this. Since the R25 bolt was somewhat stronger (22 t), an anchor length of 400 mm was also acceptable without changing the total bolt length (this is equivalent of 55 t/m).

2.2 Laboratory testing in 2021

After the 2020 tests, DSI proposed a hollow bar with greater deformation capacity (Ductile R25 with 15% deformation capacity) using a specially heat-treated steel. This bolt was compared to standard rebar bolts in the test rig at the Norwegian Technical University in Trondheim's SINTEF lab (NTNU/SINTEF).

The bolts were grouted in two independently moving concrete blocks which enables both shear tests and straight tensile tests. For both types of bolts, tests were conducted for pure tensile, pure shear and a combination of both (45° angle) (see Figure 4). The grouting medium for the hollow bar was the Mineral Bolt from DSI (two-component pumpable resin), fully encapsulating the bolt inside and out. For the rebars, the grouting medium was resin cartridges (styrene plastic). The anchor lengths were 850 to 900 mm due to spalling while drilling the holes in the concrete blocks.



(a) (b)

Figure 4 Testing at NTNU/SINTEF in 2021. (a) Diagram of test rig used; (b) Installation of bolt prior to testing

Both the hollow bar bolts with ductile steel and the rebar bolts showed similar deformation capacities in the lab tests. The rebar bolts started to deform at 16–17 t and failed at 20 t and the hollow bar bolts failed at 22–23 t. The hollow bar bolts where generally stronger in shear than the rebar bolts. One rebar bolt was pulled out of the grout during testing. See Figure 5 for the results of the hollow bar bolts.

Figure 5 **Test results from NTNU/SINTEF lab for DSI Ductile R25 hollow bar bolts. Blue lines are pure tensile, green lines are pure shear and red/orange are combination tests**

2.3 Trial of 2022

For 2022, a large-scale efficiency and method test was planned in the Renström mine using a bolting rig from Epiroc that could install hollow bar bolts with pumpable resin. 6,000 bolts were supplied by DSI for this test with properties corresponding to the bolts tested in Section 2.2 of this paper with 15% deformation capacity and a total length of 2.7 m. The resin used was Mineral Bolt from DSI.

Ahead of the main trials, a single test was to be performed to verify the results and assumptions made in the previous tests described in Sections 2.1 and 2.2. In the end, it took nine field tests and one follow-up laboratory test before the large-scale trial could proceed due to the identified issues with the anchor lengths. These trials are described in detail in the following sections.

All the test installations described in the following sections were conducted in competent rock unless otherwise stated.

2.3.1 Initial short encapsulation length testing

Trial #1 was performed as an acceptance test of the supplied bolts. Twelve bolts were tested with anchor lengths of 200, 300 and 400 mm with four bolts tested for each anchor length. The bolts were fully grouted but were decoupled using a stiff PE-hose, except for the tested anchor length (see Figure 6). The curing time for all the bolts was more than 24 hours. All field tests used a manually operated hydraulic jack with manual recording of the results.

In test #1, none of the tested bolts met the demand. The bolt that had the best result was pulled out of the resin at 15 t with 400 mm anchor length (anchor load of 37.5 t/m). Before the test was aborted, the average for the bolts was 22 t/m.

For test #2, complementary testing was done in collaboration with DSI staff. In the previous test, there were some concerns about the influence from the decoupling method, so the test method was changed so that only the tested anchor length was grouted in the rock. All bolts in the test were shortened to about 1 m before installation (tested anchor length >200 mm necessary for pull-out equipment). One bolt was tested after 12 minutes, half of the remaining bolts were tested after 1 hour, and the rest after 24 hours.

Tested anchor lengths were 450, 500 and 1,000 mm. One bolt was fully grouted using the decoupling method with a soft hose, similar to the test in 2020, for comparison.

For test #2, the bolts, at most, achieved 12.5 t at 450 mm anchor length (28 t/m). For 1,000 mm anchor lengths, the bolts reached 18–20 t before the steel started yielding. The decoupled bolt (soft hose) reached 7 t total load (3 t/m) before being pulled out of the resin.

(a) (b)

Figure 6 Test #1. (a) Installed bolts; (b) Decoupling method used

2.3.2 Investigating influences on resin and grouting properties

In test #3, the influence of the anti-rust coating (oil) on the resin was tested. Two-thirds of the tested bolts were degreased before installation. To check if the flushing grease was mixed into the resin, some tests were conducted where the hold of the machine was released immediately after pumping stopped and superfluous resin and flushing grease were dumped into a canister (see examples in Figure 7). There were also suspicions that movement of the bolt could occur if the 'curing hold' was not sufficiently long. This was tested by a very prolonged curing hold. The tested anchor lengths were 350, 400 and 500 mm. Curing time for most of the bolts was 24 hours. Due to failure in the testing jack, three bolts were tested after 48 hours. In total, the test included 13 bolts.

The bolts in test #3 reached a maximum load of 19.5 t at 400 mm anchor length after a long (>24 h) curing time. On average, an anchor strength of 38 t/m was reached before the bolt was pulled out of the resin. No bolts reached failure strength before being pulled out.

One configuration in test #3 showed promise so test #4 was done as a follow-up to get at better statistical basis. In test #4, nine bolts were tested with the same anchor length (400 mm) but with a curing time of 3–4 hours for three bolts and 24 hours for five bolts. One bolt was left untested. A 25 mm rebar and a fully decoupled bolt (using the same PE-hose as in test #1) was also tested as comparison.

In test #4, the bolts reached a maximum of 16 t at 400 mm anchor length. On average, the anchor strength was 34 t/m. Some of the bolts slid out of the resin when the clamping force was released by the machine after 40 seconds.

(a) (b) (c)

Figure 7 Determining amount of flushing grease used. (a) Measuring amount of grease while grouting; (b) Bolt filled with grease; (c) Bolt filled with resin

2.3.3 Investigating influences on steel properties and bolt geometry

In test #5, the investigation started to focus on the presence of the flushing grease inside the bolt or in the drillhole. Twelve bolts were installed using the normal procedure (no attempt to avoid grease in the grouted section of the bolt) and four bolts with 1 m length outside the rock which hoped to contain the grease outside the grouted length. The bolts were not shortened until after installation. There were also tests to determine if water present in the drillhole influenced the result. As a comparison, three standard rebar bolts (20 mm) were installed with pumpable resin. The tested anchor lengths for the hollow bar bolts were 500 mm and for the rebar bolts were 300, 350 and 400 mm. Curing times for most of the hollow bars were 24 hours except three that were tested after 3, 4 and 7 hours respectively. The rebar bolts were tested after 48 hours.

For test #5, hollow bar bolts with the centre filled with grease reach an anchor strength of 34 t/m. Bolts with resin in the centre reach on average 41 t/m. 20 mm rebar in pumpable resin reached 44 t/m.

In test #6, there were further tests on the effect of a grease-filled centre hole of the rebar. This time, anchor lengths of 400, 450 and 500 mm were tested, but now an ever longer part of the bolt was left outside the grouted part to ensure that only resin was present in the grouted section. Some bolts from another manufacturer were used as a comparison, these bolts had a different diameter (R28) and used a standard steel quality. Here the anchor lengths of 300, 350, 450 and 500 mm were tested. In total, 20 bolts were tested and 17 of those were tested after 24 hours with the remainder tested after 48 hours.

Of the tested DSI bolts in test #6, two reached failure strength at 18 and 22 t with 400 and 450 mm anchor lengths, respectively (over 45 t/m in anchor strength). This was the first successful test to achieve failure strength of the bolt. Both of these bolts were filled with resin in the centre hole (see Figure 8). A third resin-filled bolt was, however, pulled out of the resin at 20 t with 400 mm anchor length. All the bolts that were completely or partially filled with grease started to pull out of the resin when the anchor length was 500 mm or shorter.

Figure 8 First successful test. Failure strength of steel reached

An estimation of the amount of grease that was present in the centre hole of the bolts for tests #2–6 is shown in Figure 9.

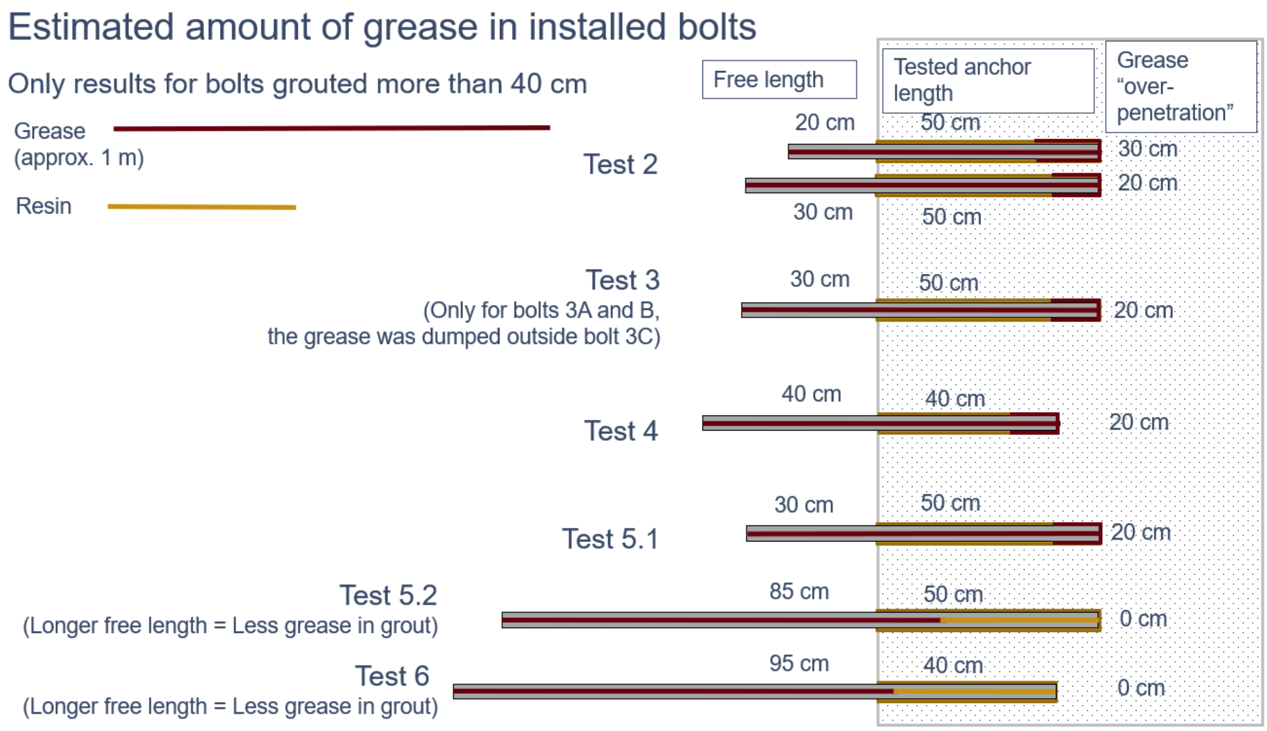


Figure 9 Grease penetration in bolts, schematic overview of tests #2–6

The bolts from other suppliers in test #6 showed similar results. At anchor length of less than 400 mm, the bolts are pulled out of the resin. One bolt filled with grease was, however, tested to failure strength at 500 mm anchor length. These bolts had different strength and deformation capacities than the bolts from DSI.

2.3.4 DSI laboratory testing

Based on the results from the tests concerning the effect of grease in the centre of the bolt, DSI conducted a set of laboratory trials. In these tests, bolts were grouted in a pair of steel cylinders with an anchor length of

1,000 mm in one and 500 mm in the other. Tests were performed both on standard and ductile steel and with or without resin in the centre hole. Two tests of each setup were performed for a total of eight tests.

During lab testing, DSI proved that 300 mm is sufficient as anchor lengths for standard steel (5%) but not for ductile steel (15%). If the bolt is filled with resin, the system as a whole is stronger, especially for the ductile steel. The failure of the ductile steel bolts was also less brittle in behaviour (see Figures 10 and 11).

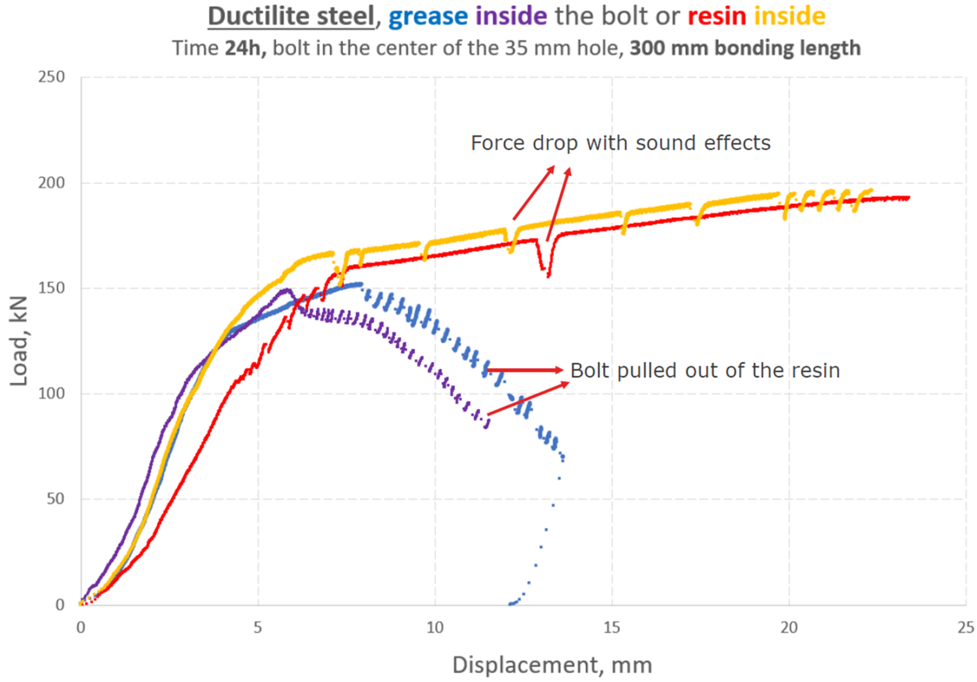


Figure 10 Results from DSI laboratory testing. Difference in deformation between centre hole filled with grease and resin in bolts with ductile steel

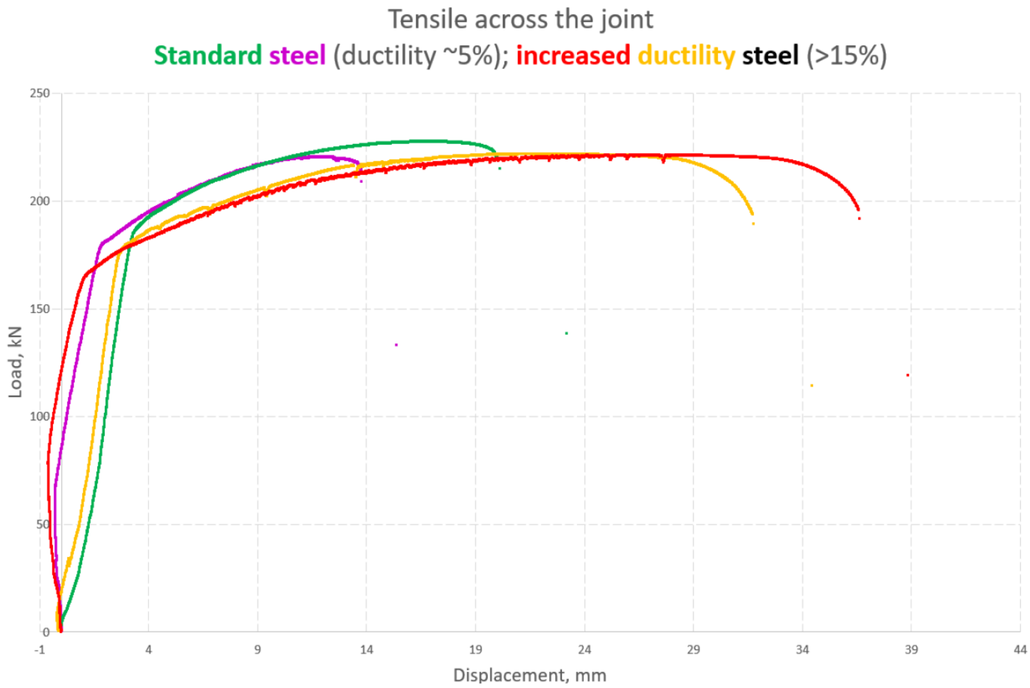


Figure 11 Results from DSI laboratory testing. Difference in deformation between standard and ductile steel with resin-filled centre holes

2.3.5 Final short encapsulation testing

In test #7, hollow bar bolts with both standard (5% deformation capacity) and ductile steel (15% deformation capacity) were tested. The anchor lengths tested were 300, 400 and 500 mm. The curing times were 2–3 hours. In total, eight bolts with standard steel and four bolts with ductile steel were tested.

In test #7, the bolts with standard steel could generally achieve higher load than the ones with ductile steel before being deformed and pulled out of the resin. The anchor strength was on average 50 t/m for standard steel and 40 t/m for ductile steel.

2.3.6 Early strength testing

In test #8, the strength after short (three hours) and long (24 hours) cure time and the effect of weak rock was tested. Ten bolts were tested in total with anchor lengths of 400, 500 and 600 mm.

After three hours of curing time in test #8, all tested bolts were pulled out of the resin. After 24 hours, only bolts with anchor length of 500 mm and above had sufficient anchor strength to be tested to failure of the steel.

For test #9, a faster-acting version of the Mineral Bolt resin was tested for early strength. The testing was conducted at two sites in the mine (upper and lower parts) to investigate the effect of rock strength. In total, 12 bolts with anchor lengths of 500 mm were tested. The curing time varied: two, five and 10 minutes and three hours were used in weak rock, and one and 20 hours in competent rock.

The bolts in test #9 were pulled out of the resin in weak rock with curing times up to three hours. In competent rock, the bolts were pulled out of the resin after one hour. After 20 hours, one bolt had sufficient anchor strength to be tested to failure of the steel.

3 Summary of results

3.1 Initial testing 2020

The results from the initial testing in 2020 are summarised in Table 1.

Table 1 Summary of results from initial testing in 2020

Tested bolt	Total number of installed bolts	Number of successful pull-out tests	Anchor length tested (mm)	Maximum load achieved (t)	Maximum anchor strength (t/m)	Average anchor strength (t/m)
'Standard' R25, weak rock	5	2	500	21.3	42.6	42.1
'Standard' R25, competent rock	6*	3	250, 500	20.6	77.8	53.7
R22	4*	3	300, 500	17.1	57	47.1
R28 dynamic	2		700	21.6	30.9	30.4

*One bolt in each test was used for torque-testing.

3.2 Laboratory testing 2021

The results from the comparative lab testing for the updated ductile R25 hollow bar and regular rebar at NTNU can be seen in Table 2.

Table 2 Average results from comparative lab testing in 2021 between ductile R25 hollow bar and regular 20 mm rebar

Tested bolt	Test type	Average yield load achieved (t)	Average ultimate load achieved (t)	Average ultimate displacement achieved (mm)
Ductile R25 hollow bar two-component silicate resin	Tensile (0°)	16.4	23.1	35.4
	Shear (90°)	5.7	21.5	43.5
	Combined (45°)	16.1	23.3	42.4
20 mm rebar B500 resin capsule	Tensile (0°)	17.3	20.5*	44.6*
	Shear (90°)	7	18.5	41.0
	Combined (45°)	12.7	20.5	32.7

*Results from only one test

3.3 Trials 2022

3.3.1 Field tests

Most of the tests used varying anchor lengths and/or anchor methods. Table 3 shows only the results for tests with short encapsulation where hollow bars with ductile steel (15% design elongation) were used. For results from the field tests where other bolt types were involved, see the description of the tests in Section 2.3.

Table 3 Compilation of test results with ductile R25 hollow bar bolts from trial in 2022

Test	Test #	Total number of installed bolts	Number of tested hollow bar bolts	Anchor length tested (mm)	Maximum load achieved (t)	Maximum anchor strength achieved (t/m)	Average anchor strength achieved (t/m)
Initial short encapsulation	1	12	6	200, 300, 400	15	37.5	22.1
	2	8	4	450, 500	12.5	27.8	22.7
Resin properties	3	13	11	350, 400, 500	19.5	48.8	38.3
	4	11	8	400	16	40	34.4
Steel/bolt properties	5	16	7/4*	500	20/22*	40/44*	34.1/40.8*
	6	20	8/4*	400, 450, 500	20/19.5*	49/50*	28/46*
Final short encapsulation	7	12	4	300, 400	18	45	41.9
Early strength resin	8	10	5/5**	400, 500, 600	16/22.5**	34/45**	28/40**
	9	14	11/3**	500	22/21**	44/42**	34.7/42**

*Results with/without grease in the centre of the bolt. **Results after <3/>20 h. Test #9 had multiple curing times.

3.3.2 DSI laboratory testing

The results from the complementary DSI laboratory testing during the 2022 trial are shown in Table 4.

Table 4 Average results from testing short embedment length and deformation capacity over single joint

Test	Test setup	Minimum embedment length (mm)	Average maximum load achieved (t)	Average ultimate displacement achieved (mm)
Influence of steel type on critical bonding length	Standard steel, resin in core	300	19.5	–
	Ductile steel, resin in core	300	20.3	–
Influence of core filling type on critical bonding length	Standard steel, grease in core	300	17.8	–
	Ductile steel, grease in core	300	15.1	–
Influence of steel type on deformation capacity	Standard steel, resin in core	500	22.5	17.0
	Ductile steel, resin in core	500	22.2	34.5

4 Discussion

Immediately at the first test in the 2022 trial, it was obvious that the bolts behaved differently than in the 2020 test, but this was also different from the laboratory tests from 2021 done with ductile steel bolts. The bolts were pulled out of the resin at a load of 15–16 t when the steel started yielding, with a characteristic popping noise when the ridges on the bolt slid out or crushed the resin.

In the complementary testing together with DSI in test #2, an even worse result was had, with large variations that could not be easily explained. The first source of errors that were investigated in test #3 was to see if the rust preventative coating (oil) affected the resin in any way, but this proved inconclusive. In this test, the first suspicions arose that the bolting rig used more grease for flushing the system than previously understood. There were also issues with the resin not curing enough to hold the bolt still after removing the clamping with the machine. A suspicion that this led to tearing in the still curing resin and a weaker final strength was another subject for test #3. Some of the tested bolts with anchor lengths of 400 mm showed promising results, but with only a few results, this configuration was once again used in test #4. But again, the variations of results were large. In test #5, it was confirmed that the flushing grease used to clean the mixer filled about 1 m length inside the centre of the bolt instead of the expected 0.2–0.3 m. The shorter cut bolts that had been used from test #2 onwards, and therefore probably had been filled with grease during testing, were again changed to a longer uncut bolt to try and keep the grease outside the anchor length.

When the error sources from excessive flushing grease inside the bolts and curing times were eliminated in test #6, the results immediately became more consistent. This was the first time during the 2022 trial that a bolt was pulled to the failure strength of the steel. These observations were then verified by the DSI lab testing; ductile steel hollow bar bolts required longer anchor lengths and were more sensitive to unfilled/grease-filled centres than normal steel. Test #7 was then done as a final short encapsulation test on site to verify the results from both the 2020 and the 2022 trials; a hollow bar bolt in ductile steel has about 10 t/m less anchor strength than one with normal steel.

For a standard rebar bolt, an average failure strength of 20 t is achieved with a 300 mm anchor length which is equivalent to an anchor strength of 60 t/m. Hollow bar bolts in ductile steel, which averaged a failure strength of 22 t, reached on average 40 t/m before the steel started yielding. When the steel deformed, the cross-section of the hollow bar bolt decreases (necking) which in turn reduced the bond between the bolt and the resin leading to a shortened anchor length, meaning that at least 500 mm of anchor length was necessary. If no resin was present in the centre hole, a longer length could yield which would then require an even greater anchor length. During installation in the trials of 2020 and the lab tests in 2021, grease was not introduced in the bolts in the same way or amount, as in the trials in 2022. If the tested hollow bar was of standard steel, the anchor strength was 50 t/m and the necessary anchor length was then 400 mm which is in line with the first tests. The larger deformation capacity of the ductile steel was still superior which led to the adoption of longer total bolt lengths in the continued trials.

It is possible that a more aggressive/square profile of the bolt's ridges/thread could be beneficial for added mechanical anchoring in the resin. An increased strength of the resin might also serve the same purpose, but both methods would reduce the deformation capacity of the bolt. If one-step bolting is used, the drill bit acts as an anchor which adds more strength, but that effect was not present in the trials described in this paper. A subsequent test with added anchors to improve the strength and allow usage of the initial, shorter batch of bolts is also not described in this paper.

In tests #8 and #9, a faster setting variant of the Mineral Bolt resin was evaluated to reduce the installation time by shortening the hold time necessary. This also had the added effect of reducing the variation in curing time due to temperature difference between different parts of the mine. No change in anchor length could be detected with this new variant. The installations for these tests otherwise used the same setup as test #6 onwards to eliminate the influence of the flushing grease.

No testing of different two-component resins with regards to strength or performance was done as a part of this trial. The only variations tested were for curing times. Normal resin consumption was around 2 litres of resin per drillhole for a standard-length bolt in competent rock but varied in fractured ground. Only a few of the short encapsulation tests recorded resin consumption in this trial.

This case proves the importance of doing in-house testing in conjunction with implementing new reinforcement elements. Without the short encapsulation tests, the bolts behaviour without resin in the centre would not have been known. In normal installation, the inner section of the bolt would have been filled with enough resin to have a functional bolt except for in the most extreme load cases (shortest anchor length/highest load from a single block) and would seldom show any faults. The outer part filled with grease would have a different behaviour than normal, but probably with better deformation capacity since this part would work as an end-anchored bolt. This benefit would also only remain if the bolt was still in contact with the surface reinforcement through the nut and plate. Re-entry is still directly after bolting and no extra curing time were added as a result from these tests.

After the testing described in this paper was concluded, the ductile R25 from DSI using Mineral Bolt pumpable resin was acceptable to Boliden in terms of deformation capacity and increased quality during installation. The bolt length was extended with 0.2 m in subsequent batches of hollow bar bolts to compensate for the longer anchor length required. The holding times have been continued to be adjusted since the test ended and are currently 20 seconds.

5 Conclusion

The property of the steel has a great effect on the anchor length, especially considering the type and geometry of the bolt used in the trials described in this paper. The ductile steel started yielding earlier than the standard steel which affected the mechanical anchoring in the resin which, in a normal installation, would lead to more of the bolt being used as an anchor and thus a shorter effective bolt length in the end. In the trial it instead led to the bolt being pulled out of the resin. If resin is not present in the centre of the bolt to act as a resisting force, an ever-larger yielded zone can occur with further negative consequences for the anchor and effective bolt length. Finally, the effect of rock temperature on the early resin properties and curing time was noticeable.

The demands for deformation capacity in the bolts meant that Boliden was willing to accept the extra anchor length necessary to use ductile steel hollow bar bolts. This capacity is vital in the lower parts of the Renström mine in areas with high stresses and/or large deformations.

For future use, the specifications for hollow bar bolt were changed to a total length of 2.9 m and a resin with faster setting times in lower temperatures was selected.

Further trials with bolting efficiency and automation continued after these tests were finished.

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