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Verifiering av ett instrument för icke-förstörande testning av bergbultars ingjutning

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REFACE

Underground constructions in rock is increasingly common in today´s society. Roads, new storage facilities, mines and tunnels in rock are constructed all over the world. These constructions need rock support to achieve a safe and stable environment. The most common rock support is to install rock bolts anchored with grout. For safety reasons, it is important to check if the rock bolts are installed in a correct manner. This can either be done through pullout tests, which is a time-consuming and destructive method, or by means of non-destructive testing (NDT). The NDT technique has been used since the late 70´s but today only a few old instruments are available.

This study is aiming at verifying the functionality and capacity of a new instrument, called the Rock Bolt Tester (RBT). The instrument has been developed over a 10 year period and is using ultrasound technique to control the integrity and quality of the grouting. The verification has included comparative measurements with the old instrument (e.g. Boltometer) and overcoring of bolts.

Additional to the authors Gunnar Rauséus provided valuable input.

The reference group has included Per Tengborg, BeFo, Mattias Roslin, Trafikverket, Marie von Matern, WSP, Johan Wiklund, Incipientus Ultrasound Flow Technologies AB, Henrik Ittner, SKB and Tommy Ellison, BESAB.

Stockholm

Patrik Vidstrand

FÖRORD

Intresset för byggande i berg ökar stadigt i dagens samhälle. Trafikleder, underjordiska lagringsutrymmen, gruvor och tunnlar byggs över hela världen. Dessa konstruktioner kräver bergförstärkningsåtgärder för att uppnå en säker och stabil miljö. Den vanligaste bergförstärkande åtgärden är att installera ingjutna bergbultar. För att säkerheten ska kunna garanteras är det viktigt att kunna kontrollera om bultarna är installerade på ett korrekt sätt. Detta kan antingen göras genom utdragstester, vilket är en tidskrävande och förstörande metod, eller med icke-förstörande provning (NDT). NDT-tekniker har används sedan slutet av 1970-talet, men idag finns endast ett fåtal fungerande instrument kvar.

Denna studie syftar till att verifiera funktionalitet och kapacitet för ett nytt instrument, kallat Rock Bolt Tester (RBT). Instrumentet, som har utvecklats under en 10-årsperiod, använder ultraljudsteknik för att kontrollera integritet och kvalitet av bultingjutningen. Verifieringsstudien har omfattat jämförande studier med det äldre instrumentet (Boltometer) samt överborrningar av bultar.

Utöver författarna har Gunnar Rauséus bidragit till projektet.

Referensgruppen har inkluderat Per Tengborg, BeFo, Mattias Roslin, Trafikverket, Marie von Matern, WSP, Johan Wiklund, Incipientus Ultrasound Flow Technologies AB, Henrik Ittner, SKB samt Tommy Ellison, BESAB.

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SUMMARY

All underground construction in rock demands rock support. The most common method today is to install rock bolts anchored with cement grout. It is of vital importance for the safety to check that rock bolts are installed in a proper and professional way by a sub-contractor. This may either be done by pullout tests, which unfortunately is a time-consuming and destructive way, or by the non-destructive testing (NDT) technique verified in this report. Today, there are only 3-4 of the old Boltometer instruments still in operation. The measurement technique is robust but old. Therefore, Geosigma initiated a project in 2010 to develop a new instrument, the Rock Bolt Tester (RBT) based on the same basic principle as the Boltometer, ultrasound technique, but with modern electronics, new communication platform, and easier operation.

The aim of the project was to verify the functionality and performance of the RBT to facilitate RBT's acceptance by the market as well as the Swedish Transport Administration (Trafikverket) as a complement and possibly replacement for the Boltometer. The project has included comparative measurements with the Boltometer and the RBT on about 100 rebar bolts as well as overcoring of some bolts with defects in the grouting.

The results of the comparative measurements in Dannemora mine, Äspö Laboratory and Stockholm Bypass, show that the RBT is more sensitive than the Boltometer to the defects occurring in the grouting and also that the methods give similar results. The overcoring, even though performed for a limited number of bolts, showed that RBT is sensitive even for small defects in the grouting. The tests performed on combination bolts, like the PC-bolt and CT-bolts that were installed at Äspö HRL, gives promising results but much more tests are needed to verify the RBT's functionality on these bolt types. This may also be a new application area for the RBT in the near future.

Keywords: Rebar bolts, ultrasound measurement, Non-Destructive Testing, NDT, rock support, grouting, overcoring

SAMMANFATTNING

Allt byggande i berg kräver förstärkningsåtgärder. Idag är den vanligaste förstärkningsåtgärden att installera bergbultar som förankras med cementbaserat bruk. Det är av stor betydelse för säkerheten att kontrollera att entreprenören gjutit in bulten på ett korrekt sätt. Detta kan göras antingen genom utdragstester (förstörande provning) eller med icke-förstörande provning (NDT) som beskrivs i denna rapport. Det finns idag endast 3-4 Boltometrar kvar i Sverige som fungerar. Tekniken och elektroniken är visserligen robust men föråldrad. Geosigma startade därför ett arbete under 2010 i syfte att ta fram ett nytt instrument, Rock Bolt Tester (RBT), baserat på samma grundprincip som Boltometern, ultraljudsmätning, men med modern elektronik och kommunikationsplattform och lättare handhavande.

Syftet med detta projekt har varit att verifiera RBT:s funktionalitet och prestanda så att RBT kan accepteras av marknaden och Trafikverket som komplement och trolig ersättare till Boltometern. Projektet har inkluderat jämförande mätningar med Boltometer och RBT på ett hundratal kamstålsbultar samt överborrning av ett antal bultar med defekter i ingjutningen.

Resultaten från jämförande tester i Dannemora, Äspölaboratoriet och Förbifart Stockholm visar att RBT är känsligare för defekter i ingjutningen än Boltometer, men också att överensstämmelsen mellan metoderna är mycket god. Överborrningen som gjordes på tre bultar i Äspölaboratoriet kunde tydligt visa att de defekter RBT identifierar också existerar i de överborrade kärnorna. Tester på kombinationsbultar (CT-bult och PC-bult) ger också lovande resultat, men mer tester behövs på dessa bulttyper. Detta kan också vara en ny applikation för RBT inom en nära framtid.

Nyckelord: Kamstålsbultar, ultraljudsmätningar, icke-förstörande testning, NDT, bergförstärkning, ingjutning, överborrning

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1. BACKGROUND AND AIM

1.1 Introduction

The most common type of rock support elements are rock bolts that are grouted to the rock using cement grout or epoxy. It is of vital importance to check that rock bolts are installed in a proper and professional way by a sub-contractor. This may either be done by pullout tests, which unfortunately is a time-consuming and destructive way, or by the non-destructive testing (NDT) technique verified in this report (Song at al. 2017).

Pullout tests are still used but it has been shown by Li et al. (2016) that the grouting length in the range of only 25 to 36 cm was sufficient for a 20 mm rebar bolt to pass such test. This means that an extremely bad grouting would still pass the test.

The NDT technique for testing rock bolts was developed in the 70s by the company Geodynamik AB (Thurner, 1988). The instrument, which was named Boltometer is still used for the NDT of rock bolts when building new rock constructions in Sweden, however, only three-four instruments are still in operation. The technique and electronics of the Boltometer is robust but old and not commercially available any more. Therefore, in 2010 Geosigma AB started a research project with the aim to develop a new instrument, Rock Bolt Tester (RBT).

The idea was to use the same basic measurement principle of as that implemented in the Boltometer, i.e., propagation of guided ultrasonic waves, but realized by means of modern electronics, digital filtering and communications on PC platform. The goal was to develop a more easy-handled, efficient, and sensitive instrument than the Boltometer, which could complement and finally replace the Boltometer on the market. The development of the RBT has been done in close cooperation with Trafikverket, Statens vegvesen, Boliden and LKAB. A number of prototype instruments have been tested and bolts with pre-prepared defects in the grouting have been installed in four rock facilities with somewhat different geology (Dannemora Mine, Äspö Hard Rock Laboratory, Roslagsbanan and Citybanan). However, the two latter facilities were not available for tests within this project.

The final version of the RBT is now available. Earlier tests, as well as the tests performed within the current project, have shown that RBT has a higher sensitivity and gives more distinct indications than the Boltometer. There is however, a certain misbelief in the rock building society against the NDT and if it really works. This is possibly an effect of some experiences from the old instruments and/or wrong handling of the instruments or the registered data. This project was initiated to clarify those issues and its results should build up confidence to the investigated NDT technique as a proper tool for quality inspection of the rock bolt installation process.

1.2 Aim

The aim of the project is to verify the functionality and performance of the RBT to facilitate RBT's acceptance by the market as well as the Swedish Transport Administration (Trafikverket) as a complement and possibly replacement for the Boltometer.

1.3 Scope of work

The capacity of the RBT to detect and identify defects in the cement grouting surrounding fully grouted rock bolts has been done by direct comparison between the Boltometer's and the RBT's measurements performed on the same bolts and by over-coring the bolt installations that have been identified as defective by means of the RBT's indications.

The comparative measurements in this project have been performed at three different locations on pre-prepared bolts as well as ordinary rock support bolts:

- Dannemora mine, central Sweden (pre-prepared bolts)
- Äspö Hard Rock Laboratory (HRL), southern Sweden (pre-prepared bolts and ordinary rock support)
- Access tunnel at the Stockholm bypass project (ordinary rock support)

At Äspö HRL, 43 ordinary bolts were controlled using both the Boltometer and the RBT. Afterwards, 10 of the inspected bolts were selected for the over-coring operation, which was documented for comparison with the data obtained from the instruments. However, changes in planning at Äspö HRL as well as the availability and capacity of the involved drilling companies hindered the original plan, so in the end, only three bolts could be over-cored within the given time frame and budget of this project.

2 MEASUREMENT PRINCIPLE AND METHODOLOGY

2.1 Measurement principle

Guided waves (GW) are the ultrasonic elastic waves that propagate in solid media limited by hard boundaries, for instance, plates, bars and tubes. Guided waves have more complex physical nature than the bulk waves (longitudinal (L) and shear (S) waves) commonly used in ultrasound NDT. Their use in the NDT applications is limited by their complex physical features – mainly by the fact that they are multimodal and dispersive. This means that, in a general case, a guided wave pulse that propagates in a bar consists of a number of wave modes that propagate simultaneously with different velocities, which are frequency dependent, see Fig.1-1. Each wave mode is related to a specific particle movement, the basic modes are: compressional, torsional and flexural. If a short pulse of a dispersive wave mode propagates in a bar the dispersion effect will cause its deformation, i.e., the pulse will be stretched in time and its envelope (shape) will be irregular; the longer propagation length the more pronounced the dispersion effects will be.

GWs are used especially for inspection of structures where the bulk waves cannot propagate over longer distances, typically for testing tubes (pipelines), bars and plates. Obviously, only well skilled operators who have been trained to understand their features are able to perform an effective inspection using GWs.

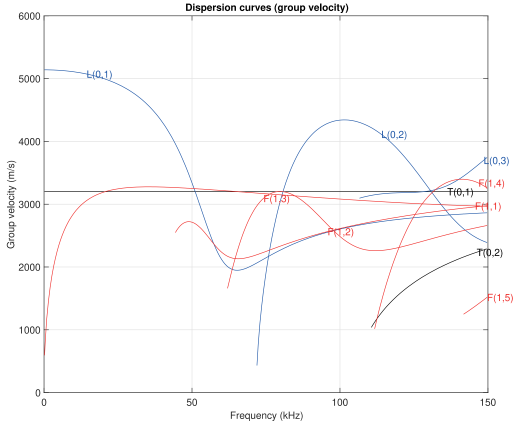


Figure 1-1. Velocities of different wave modes of a 1" steel bar in air plotted as functions of frequency.

The use of guided waves for rock bolt inspection has been investigated by a number of researchers, (e.g., Thurner 1988, Beard and Lowe 2003, Buys at al. 2009, Han et al. 2009, Stepinski and Mattsson 2014 and 2016) and found to be a useful way to detect the grout condition around a rock bolt.

Operation principle of a setup used for rock bolt testing is illustrated in Figure 1-2. An application tailored ultrasonic transducer, which operates in a pulse-echo mode, is excited by high-energy pulses from the instrument, which evoke guided waves that propagate in the steel bolt embedded in grout. The generated waves propagate forwards along the bolt, and if discontinuities are present at the bolt surface, they can be reflected as echoes propagating back to the transducer. A part of the wave energy leaks to the grout and further to the surrounding rock resulting in an energy loss that appears as a length-dependent attenuation of the echo signals propagating in the bolt. The attenuation depends on the acoustic properties of the grout; for steel rock bolts it is lower for an epoxy grout than for the cement grout commonly used in Scandinavia. An echo signal formed by the reflections from the discontinuities at the bolt and its vicinity (e.g., break, air pockets or corrosion) as well as at the bolt end, is received by the sensing element of the transducer.

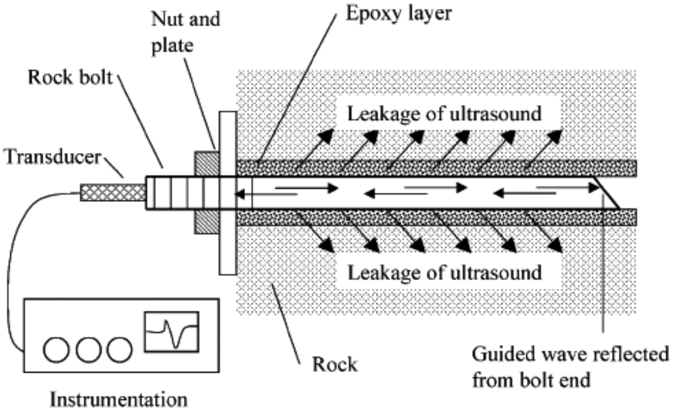


Figure 1-2. Schematic diagram of the rock bolt test setup and the measurement principle.

2.2 The Rock Bolt Tester (RBT)

The RBT is a PC based instrument that contains a specially designed, digitally controlled analog electronics and a DAQ (Data Acquisition) card for sampling and converting signals to digital form (Stepinski and Mattsson 2014 and 2016). The analog electronics consists of the signal generator and signal receiver boards connected as illustrated in the block diagram in Figure 2-1.

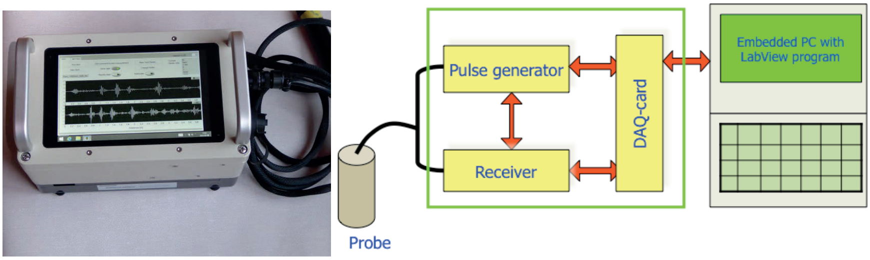


Figure 2-1. The portable, battery supplied RBT instrument (left), and its simplified block diagram (right).

The analog boards are connected to the DAQ card, which performs acquisition and digitalization of the analog signals received from the specially designed probe and from the communication with the PC.

The programmable pulse generator is capable of emitting high-energy long pulse trains. The pulse trains with amplitude of 30V can be loaded to the RBT in a digital form and saved in the PC. The pulses have the form invented for radar technique – a broadband sine wave with variable frequency (chirp). Such pulse trains can be converted by means of a matched filter to a high amplitude short pulse. Two separate pulse sequences generate the compressional (L) and quasi-flexural (F) waves in the bolt. The programmable receiver has two separate channels capable of amplifying small echo signals received by the mode sensitive probe. The application tailored RBT's probe contains, integrated into a single handle, two pairs of broadband piezoelectric stack elements, one pair operates as a transmitter and the second as sensor. An echo signal formed by the reflections from the discontinuities in the bolt and grout is received by the sensor pair of the probe that is mode-sensitive, i.e., it has a limited ability to distinguish between the L and F modes.

It appears that both wave modes propagate with different velocities and are sensitive to different types of flaws. Note that guided waves are dispersive and velocities of the L and F wave modes depend on the state of rock bolt's grouting, i.e. velocities in the bare rod are considerably higher than those in the grouted one. This means that, due to the law of physics, those velocities are only approximately known and mapping between time and bolt length is only approximate.
The problem related to the high signal attenuation in the grouted bolt has been solved by two means: firstly, high energy, wideband pulse trains are transmitted, and the resulting echoes are captured by the sensitive piezoelectric elements and amplified by the high gain receiving channels. Secondly, the received signal is processed by the digital matched filters that perform pulse compression, which results in a considerable increase of the signal to noise ratio.

An example of the raw signals, registered for a partly grouted 2 m long rock bolt is shown in the upper panel of Figure 2-2 (Stepinski and Mattsson, 2016). It can be seen that the filtered signals, shown in the lower panel, feature much higher amplitudes and signal to noise ratio than the raw ones. The large pulses at 1.8 m in the lower panel are the reflections from the bolt end while the small echoes seen at approx. 4 m are the double end reflections.

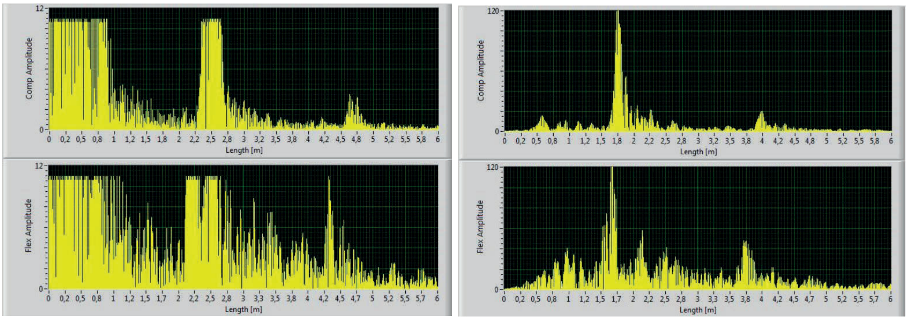


Figure 2-2. Example of ultrasound echo signals registered and displayed by the RBT instrument. Raw signals before filtering (a), and the signals processed with matched filter (b). The compressional signals are shown in the upper panels and the flexural signals in the lower panels.

The length of a bolt may be determined if the velocity of the ultrasound wave in steel is known. Generally, velocity of guided waves depends on the mode type and frequency, and for rock bars also on the grouting type, its thickness and the surrounding rock type (Beard, Lowe, 2003, Stepinski and Mattsson, 2016). Also the amplitude of the echo, caused by a defect in the grouting, depends on many factors, like rock type, water content in the grouting (vct) and bolt type. It is therefore recommended to calibrate the RBT instrument on each site in terms of the signal strength (energy) and its length indication by measuring a perfectly grouted bolt with known length.

Both the Boltometer and the RBT are designed to detect defective grouting of ordinary rebar bolts, Ø 20-25 mm and lengths up to maximum 4-6 m. Other common types of bolts are the combination bolts, like CT-bolt and PC-bolt, which have an expansion shell in the bottom that is expanded directly to take load prior to grouting. In mines, dynamic bolts, like the D-bolt, are frequently used as they are specially designed to absorb kinetic energy and resist deformations in the rock. This project has been focused on the rebar bolts, but there are also a few tests with the RBT on the CT- and PC-bolts that look promising, cf. Chapter 3.

2.3 Test methodology

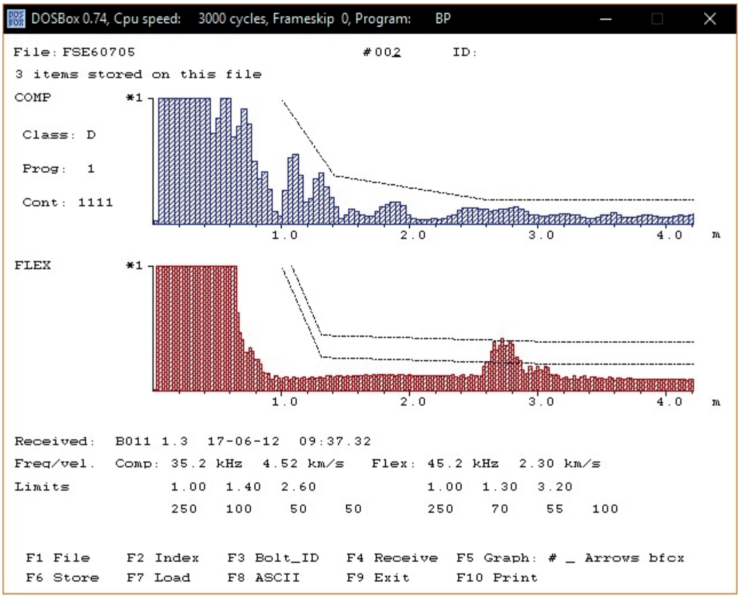
Before the actual measurement is done, the plate and nut of the rock bolt should be removed. If the plate and nut could not be removed, the ultrasound signal might be heavily dispersed and weakened. The bolt end then has to be grinded perpendicular to the bolt axis to achieve a smooth and clean surface that facilitates transmission of the ultrasound signal, see Figure 2-3.

Figure 2-3. Grinding of the bolt end.

A contact agent, silicon or cupper paste is applied at the bolt end and the RBT probe is fixed to the bolt end by magnetic force from the permanent magnets integrated inside the probe. The actual measurements shall be repeated 6 times by rotating the probe in 6 angular positions with approx. 60° interval and pressing the transmitter button. The same test methodology was applied for the comparative Boltometer tests with the exception that the probe had to be fixed by hand to the bolt end.

2.4 Test result evaluation with the Boltometer

The evaluation of the echograms from the Boltometer test is based on the amplitude thresholds of the ultrasound echo that are labeled from A to D. If the amplitude in one of the 6 measurements exceeds a pre-determined classification line, given by a reference bolt, which is assumed to be perfectly grouted, then the rating is lowered one or more grades (e.g. from A to D), see Figure 2-4.



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3 items stored on this file
COMP
 Class: D
 Prog:  1
 Cont: 1111
FLEX

Received:   B011 1.3  17-06-12  09:37.32
Freq/vel.   Comp: 35.2 kHz  4.52 km/s   Flex: 45.2 kHz  2.30 km/s
Limits            1.00  1.40  2.60              1.00  1.30  3.20
                  250   100    50    50         250    70    55   100

 F1 File    F2 Index   F3 Bolt_ID   F4 Receive   F5 Graph: # _ Arrows bfcx
 F6 Store   F7 Load    F8 ASCII     F9 Exit      F10 Print
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Figure 2-4. Echogram from a measurement with the Boltometer. The upper blue bars represent the echo amplitude from the compressional wave (Comp) and the lower red bars from the flexural wave (Flex). The black classification lines are crossed and the bolt is classified as a D-bolt (insufficient function).

The classification line is placed just above the amplitude from the reference bolts, which implies that a measurement will indicate if the bolt is less well-grouted than the reference bolt. The echogram in Figure 2.4 shows that there is a high level of inherent noise in the measurements of the first 1,4 m of the bolt, which makes it difficult to evaluate that part.

The results of the measurements are divided into four classes, A=satisfactory function, B=reduced function, C=defective function, D=insufficient function. In practice, this division means that C- and D-bolts need to be replaced or complemented by a new bolt, while A- and B-bolts are good enough. However, many B-bolts in the same area may require additional bolting. These decisions are project specific. Note that the Boltometer should be calibrated and its classification thresholds should be adjusted before measurements are carried out at each new site. The calibration procedure can be correctly accomplished if perfectly grouted reference bolts are available for this purpose at each site.

2.5 Test result evaluation with the RBT

The evaluation of the echograms from the RBT is based on the signal power, or energy, of the echo rather than the amplitude. The six different measurements performed on each bolt are all simultaneously presented in the echogram in different colors, see Figure 2-5.

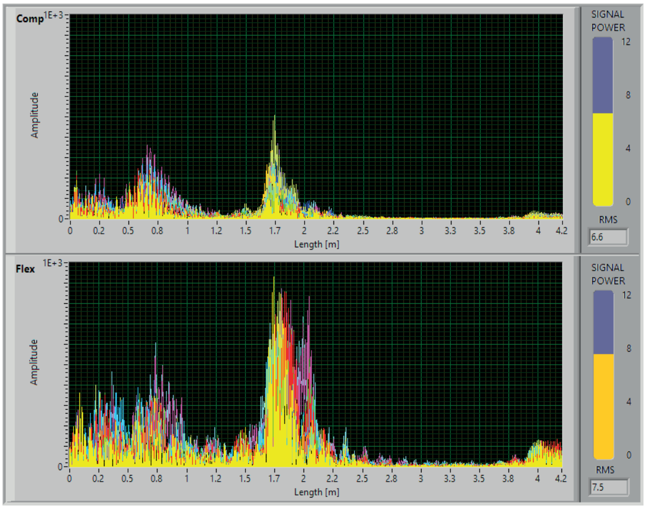


Figure 2-5. Example results from the RBT measurement for Comp (upper panel) and Flex waves (lower panel). Each color represents one measurement angle on the same bolt. The colored bars and small windows to the right display the relative total energy of the received signal in dB. The latter values depend on the reference bolt used for the calibration.

Additionally, the relative signal power is displayed in logarithmic scale (dB) as a color bar seen to the right of the echogram. Logarithmic scale is commonly used in electrical engineering thanks to its two main features – both large and small values can be seen in a log-scale and multiplication is performed by adding dB values. RBT is calibrated in power decibels as $P_{dB} = 10log\left(\frac{P_S}{P_r}\right)$, where P_S is the measured signal power and P_R denotes power of the bar used as a reference. The color bar scale is from 0 ($P_S = P_r$) *to 12dB*, which corresponds to ($P_S = 16P_r$).

For each specific measurement the relative signal power is determined as a root-mean-square (RMS) of all sampled amplitudes within preset length interval, divided by the RMS of a well-grouted reference bolt. Note that the instrument's sampling period is 4 µs, which corresponds to approx. 16mm bolt length at wave velocity 4000m/s.

RMS is commonly used as a measure of signal power, it is calculated as a root of sum of squared signal amplitudes in a defined time interval; for a discrete signal it corresponds to the sum of N samples in the chosen interval, according to

$P_{RMS} = \sqrt{\sum_{i=0}^{N} s_i^2}$, where s_i are the signal samples in the chosen interval.

The RMS power index implemented in the RBT is flexible and enables the operator choice of the length interval, which is important for the test result. For instance, the operator can disregard the first part of the signal that may be characterized by high amplitudes, which are irrelevant for the test, and focus on the deep part of the echo signal where strong echoes normally appear if the rockbolt's hole was not properly filled with grout.

One reason for choosing the energy instead of the amplitude, as for the Boltometer, is that one discontinuity may result in locally high amplitude but if there are more discontinuities, the waves will be scattered, and the amplitude will be spread over the echogram with lower amplitudes. This means that the same defect in the grouting may result in different amplitudes, depending how the waves have propagated on their way through the bolt.

If properly used, the bolt classification using the RMS value, implemented in the RBT, is more advanced and flexible than that used in the Boltometer, which means that it may vary in the same way as for the Boltometer's classification between different rock types, grouting material, water content, etc. Note, however, that it requires the initial calibration at each site, and it motivates the operator's active role. Therefore, it is highly recommended to adjust the classification limits individually for each site. As for the Boltometer, it is recommended that at least one or two perfectly grouted reference bolts are prepared at each site. Moreover, since the reference RMS is evaluated for preset length intervals, it is also possible to choose reference different RMS values for each individual measurement, e.g., the reference RMS for the whole length and another one for an interesting part of the bolt length. In this way the initial high signal amplitudes that may occur at the first part (0 to 0.5m) of the bolt due to the influence of, for instance, the un-removed plate can be suppressed and relatively large echoes or noise are pronounced in the outer part of the bolt.

In the comparative measurements presented in this report, a classification system similar to the Boltometer has been applied, i.e., Classes A-D, see Section 2.4. The RBT is much more sensitive than the Boltometer, which also means that the classification limits vary much more and have to be established individually for each site.

3 RESULTS

3.1 Comparative measurements on prepared reference bolts

3.1.1 Dannemora mine

Dannemora is an old iron mine located in Uppland in central Sweden. The mining operation was shut down in 2015 but there is still some limited access to the mine. In total 22 ordinary rebar bolts, Ø 25 mm, quality B500BT, with threaded end M24×150 were prepared with different defects and installed at the 145 m level in 2012. The bolts with lengths between 2.0 and 3.5 m are installed in limestone, see Figure 3-1.

The basic idea behind the prepared test bolts was that the most common defects in the grouting are caused by the failure to insert the pump hose into the bottom of the borehole, alternatively by the water-cement ratio (vct) being too high, which leads to the grout slipping out of the hole. In both cases, a cavity should be formed in the bottom of the hole. Other possible scenarios could be that a water conducting fracture intersects the borehole somewhere causing partial out-washing of the grout.

The defects on the test bolts were made by shielding a part of the bolt with a plastic tube sealed with silicon in both ends to prevent grout from entering space between the bolt and tube, see Figure 3-2. Plastic end cups were also installed on some of the bolts to create uniform conditions for producing the end echoes.

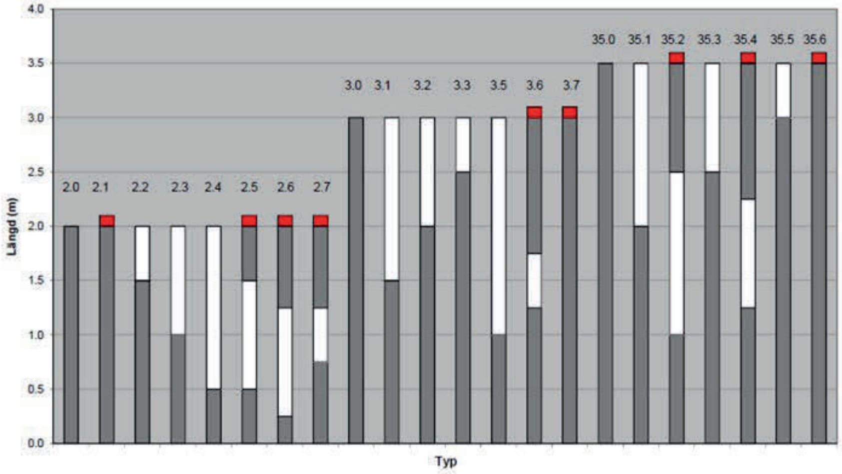


Figure 3-1. Schematic drawing of prepared bolts in Dannemora. White color illustrates the prepared parts, whereas grey are the grouted parts and red shows where end cups have been installed.

The results summarized in Table 3.1, show a very good correlation between the Boltometer and the RBT. RBT shows high dB-values for all the D-classified bolts by the Boltometer and marked echoes and are classified as C- or D-bolts also with RBT. Notable is that one of the bolts without prepared defect, i.e. the bolt 2.0, which has been classified as a D-bolt by both the RBT and Boltometer. Otherwise there is only one major difference among the 22 bolts, namely, the bolt 3.0, which is classified as a D-bolt by the RBT and A-bolt by the Boltometer.

Figure 3-2. Preparation of defects and end plug (to the right) on ordinary rebar bolts.

Table 3.1. Comparison of the measurements obtained from the Boltometer and RBT. Bolt 35.0 was chosen as a reference bolt.

Bolt no	**RBT Comp dB**	**RBT Flex dB**	**RBT class***	**Boltometer class**	**Good bolt**	**Air pocket length (m)**	**End cap**
2.0	3.6	6.4	D	D	Yes	-	-
2.1	6.2	7.7	D	D	Yes	-	Yes
2.2	5.8	7.0	D	D	-	0.5	-
2.3	5.3	2.9	C	C	-	1.0	-
2.4	6.3	9.0	D	D	-	1.5	-
2.5	7.2	6.6	D	D	-	1.0	Yes
2.6	7.6	8.9	D	D	-	1.0	Yes
2.7	5.2	6.8	D	D	-	0.5	Yes
3.0	6.2	5.2	D	A	Yes	-	-
3.1	6.5	7.3	D	D	-	1.5	-
3.2	6.3	8.2	D	D	-	1.0	-
3.3	5.7	6.6	D	C	-	0.5	-
3.5	6.0	6.6	D	D	-	2.0	-
3.6	4.9	5.4	C	D	-	0.5	Yes
3.7	4.5	5.2	C	C	Yes	-	Yes
35.0	0	0	A	A	Yes	-	-
35.1	3.1	6.8	D	D	-	1.5	-
35.2	3.7	6.4	D	D	-	1.5	Yes
35.3	7.6	9.9	D	D	-	1.0	-
35.4	5.0	5.9	C	C	-	1.0	Yes
35.5	4.7	6.3	D	C	-	0.5	-
35.6	3.1	3.5	A	A	Yes	-	Yes

*Classification limits: A= >4, B= 4.0-4.9, C= 5.0-5.9, D= >6

Figures 3-3 and 3-4 show two examples of echograms from the reference bolt 35.0 and bolt 35.3 with a prepared 1.0 m defect at the end of the bolt. The reference bolt 35.0 shows very low echoes both for the Boltometer and the RBT while the prepared bolt 35.3 with a 1 m air pocket in the inner part gives high echoes and high energies.

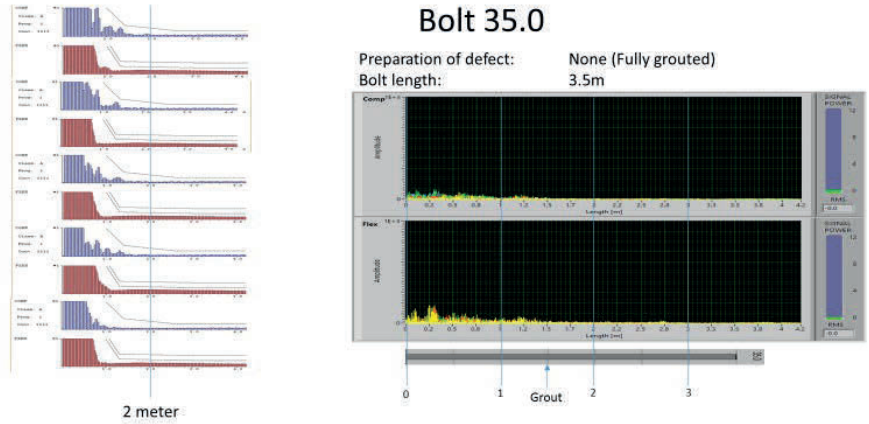


Figure 3-3. Reference bolt 35.0 at Dannemora. Echograms from the Boltometer (left) and from the RBT (right). (6 measurements performed with both instruments).

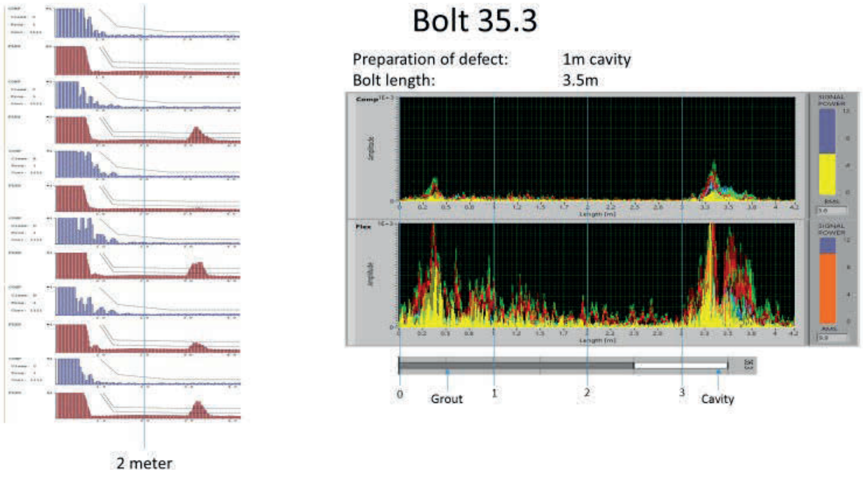


Figure 3-4. Bolt 35.3 at Dannemora. Echograms from the Boltometer (left) and from the RBT (right). (6 measurements with both instruments).

3.1.2 Äspö Hard Rock Laboratory (HRL)

Äspö HRL is an underground facility built for the research and development of methods for final disposal of radioactive waste. The facility has been operated since the early 90´s is owned by the Swedish Nuclear Fuel and Waste Management Co (SKB).

In total 21 bolts were prepared with different defects and installed in tunnel TASP at the level 410 m in 2017. The bolts with lengths between 3.0 and 4.0 m were installed in granitic rock, see Figure 3-5. The bolts were of three different types: CT-bolts (no 1:1-1:3), PC-bolts (no 2:1-2:4) and ordinary rebar bolts (no 3:1-4:7) of which CT-bolts and PC-bolts are combination bolts. Two of the combination bolts (1:3 and 2:4) were installed without expansion shell to analyze the possible effect of the echo from the expansion shell. The defects were prepared in the same manner as described in Chapter 3.1.1.

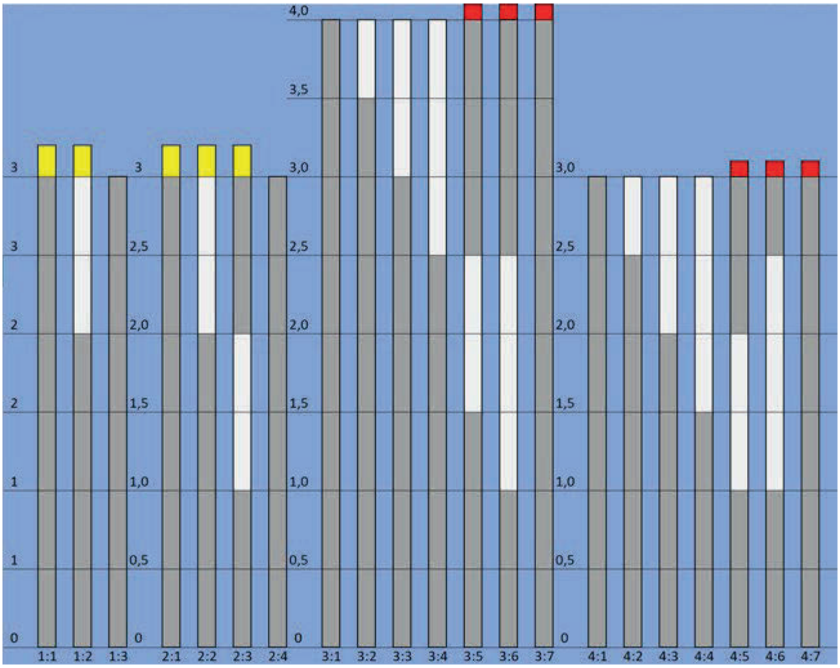


Figure 3-6. Schematic drawing of the prepared bolts at Äspö HRL. White color illustrates the prepared parts whereas the grouted parts are grey, and red shows where the end cups have been installed. Yellow shows bolts with anchors (PC and CT-bolts).

The results, presented in Table 3.2, are somewhat unexpected. The reference bolts for 3 and 4 m long rebar bolts have a distinct end-echo or overall high amplitudes compared to the normal reference bolt. This indicates that some defect may have occurred in the grout during the grouting process. Because of the strong echoes for the reference bolts almost all rebar bolts were classified as A-bolts by both instruments. The combination bolts give better echoes and promising results, especially, for the PC-bolt, although they make up a very small statistical sample. There may be several reasons for these low levels of the response echoes, however, other measurements performed on rebar bolts at Äspö, see Chapter 3.2.2, resulted in much higher echoes.

Table 3.2. Results from the comparative measurements obtained using the RBT and the Boltometer at Äspö HRL.

Bolt id	Bolt length (m)	Defect from	Defect to	Length of defect (cm)	End plug	Expansion shell	Class Bolto-meter	RMS Comp dB	RMS Flex dB	Class RBT
CT-bolt										
1.1	3.00	-	-	-	-	Yes	C	0.0	0.0	A
1.2	3.00	185	285	100	-	Yes	A	1.6	4.0	C
1.3	3.00	-	-	0	-	No	C	2.9	4.6	D
PC-bolt										
2.1	2.82	-	-	0	-	Yes	A	2.4	2.1	B
2.2	2.82	167	267	100	-	Yes	C	7.5	5.8	D
2.3	2.82	100	200	100	-	Yes	A	5.8	2.5	D
2.4	2.82	-	-		-	No	A	0.0	0.0	A
Rebar bolt 3m										
3.1	4.00	-	-	-	-	-	A	0.0	0.0	A
3.2	4.00	350	400	50	-	-	A	0.5	0.5	A
3.3	4.00	300	400	100	-	-	A	1.9	1.1	A
3.4	4.00	250	400	150	-	-	A	1.4	1.8	A
3.5	4.00	150	250	100	Ja	-	A	-2.9	-4.4	A
3.6	4.00	100	250	150	Ja	-	A	-5.6	-5.0	A
3.7	4.00	-	-	-	Ja	-	A	-1.8	-2.0	A
Rebar bolt 4m										
4.1	3.00	-	-	-	-	-	A	3.4	3.0	C
4.2	3.00	250	300	50	-	-	A	3.0	2.1	C
4.3	3.00	200	300	100	-	-	A	-0.8	-1.2	A
4.4	3.00	150	300	150	-	-	D	1.5	1.2	A
4.5	3.00	100	200	100	Ja	-	A	-2.0	-1.6	A
4.6	3.00	100	250	150	Ja	-	A	2.1	2.2	A
4.7	3.00	-	-	-	Ja	-	A	0.0	0.0	A

There are, however, some differences in the drilling and grouting procedures, compared to standard procedures that possibly have influenced the measurements. Firstly, the bolt holes were larger than the normally used diameter, i.e. 64 mm compared to 48 mm, for the bolts 2.2, 3.5, 3.6, 4.5 and 4.6, which are also the rebar bolts generating very low level echoes. Secondly, the installation was carried out by installing the bolt prior to filling the borehole with grout, which is normal procedure for the combination bolts, but not for the rebar bolts. The third difference is that the concrete pump was not working properly and the filling of each hole took a very long time, up to 90 minutes per bolt hole, and it cannot be excluded that grout may have entered the air-filled space between the steel bar and the plastic tube or that cavities was unintentionally created by the concrete pump pressing air pockets into the grout. All these differences may have influenced and possibly dampened the echoes.

The echograms for the Boltometer and the RBT for the PC-bolts 2.2 and 2.4 are shown in Figure 3-7. The defect bolt 2.2 produced high echoes, but their length indication is incorrect. This is possibly an effect of the complex geometry of the bolt compared to a rebar bolt. Note that the Boltometer also indicated some small echoes at the same bolt length indication.

Figure 3-8 shows the comparison between the “good” bolt 3.1 and the bolt 3.4 with a large defect in the bottom of the hole. The RBT, but not the Boltometer, show echoes at the end of the good bolt (3.1), but not big enough to be classified as B-D-bolts. This may be an effect of insufficient grouting at the end of the bolt. This affects the classification of all 3.x bolts, since the reference bolt 3.1 is most likely not fully grouted.

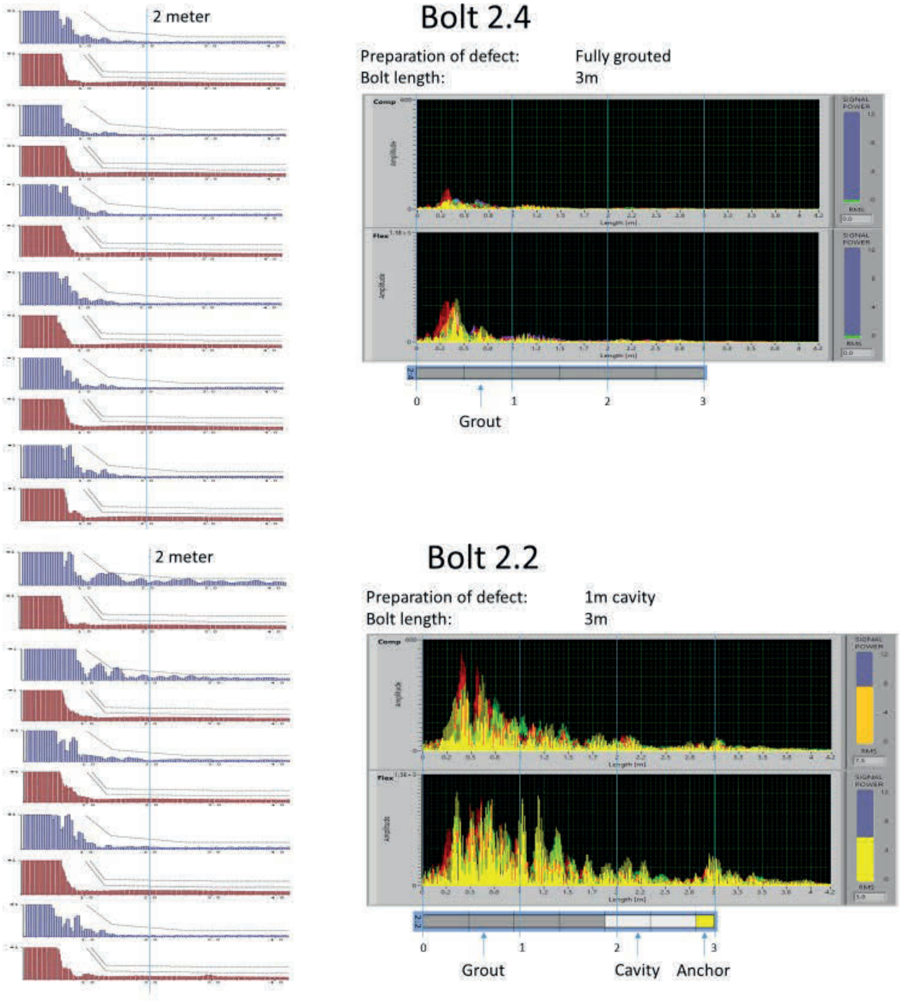


Figure 3.7. Echograms obtained for the PC-bolts 2.4 (upper) and 2.2 (lower) from the Boltometer (left) and from the RBT (right) (6 measurements performed with both instruments).

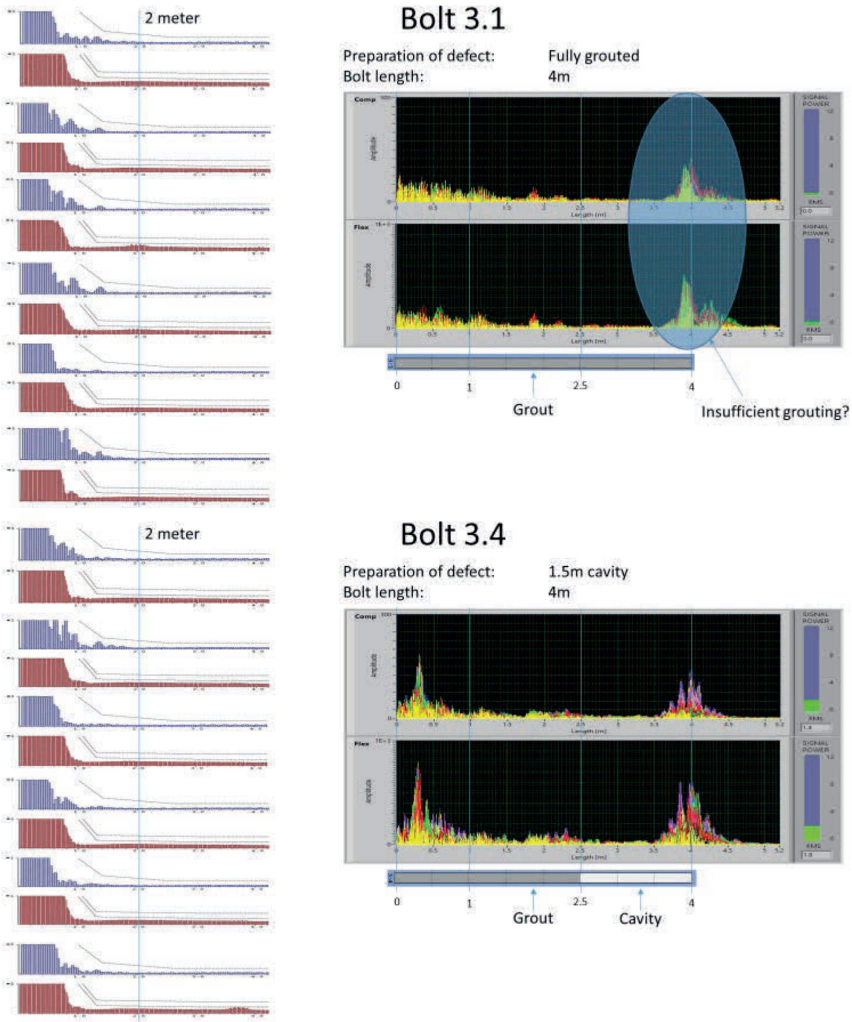


Figure 3-8. Echogram obtained for the rebar bolts 3.1 (upper) and 3.4 (lower) from the Boltometer (left) and from the RBT(right). (6 measurements performed with both instruments).

3.1.3 Previous measurements

The development of the RBT has earlier also involved more than 1000 measurements at two other sites with prepared bolts, Citytunneln and Roslagstull in Stockholm. However, these sites are currently inaccessible since they are in use for traffic. Comparative measurements have been performed with earlier versions of RBT that resulted in more qualitative than quantitative comparisons.

3.2 Comparative measurements on unprepared bolts

3.2.1 Stockholm Bypass

Stockholm Bypass is a series of underground expressway tunnels currently under construction between the Kungens Kurva interchange in the south of Stockholm and the Häggvik interchange north of Stockholm. Most of this bypass, i.e. more than 17 out of 21 kilometers, is built underground. In one of the access tunnels, measurements were carried out on 41 ordinary rebar bolts both with the Boltometer and the RBT.

The results presented in Figure 3-9 and in Appendix A and B show that the RBT measurements resulted in large echoes and high RMS for all bolts that have been classified as B-D bolts with the Boltometer. There are also high echoes from 5-6 other bolts that are classified as A-bolts with the Boltometer but are classified as B-D bolts with the RBT. In total, 35 of the 41 bolts are classified the same or within one grade by both instruments. Seven bolts are classified as C or D-bolts with the Boltometer, and twelve with the RBT. Visual inspection also showed that five of the bolts were lacking grout in the outer part of the bolt hole, 1-2 m from the wall. Only two of those were classified as D-bolts with the Boltometer and four as D-bolts with the RBT. This also verifies that the RBT is more sensitive to the outer part of the bolt than the Boltometer. The RMS values are significantly higher than at Dannemora and Äspö, possibly due to the differences in rock type, water content, etc.

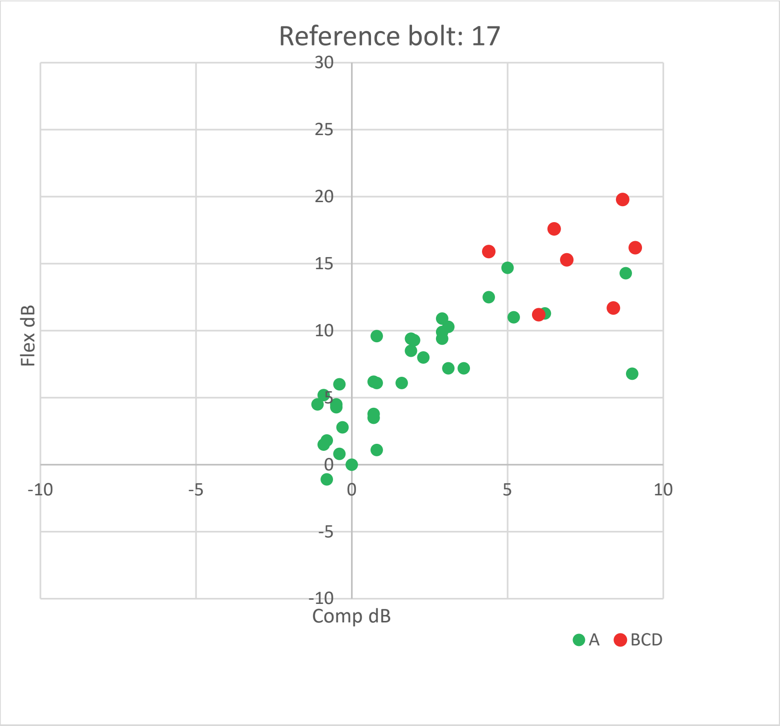


Figure 3-9. Comp and Flexwave energies in dB for 41 bolts in Stockholm bypass when bolt #17 served as a reference bolt. Green dots represent bolts that were classified as A-bolts with the Boltometer and red dots as class B-D.

3.2.2 Äspö HRL

Comparative measurements have been performed at Äspö HRL on 43 bolts in three access tunnels at the depths 410-460 m (TASP, TASU, TASS and TASJ). The aim of the measurements was also to determine which bolts that were suitable to overcore within this project. The bolts in TASS were later found to be short combination bolts (2 m) while the rest were ordinary rebar bolts with lengths 3 – 4 m.

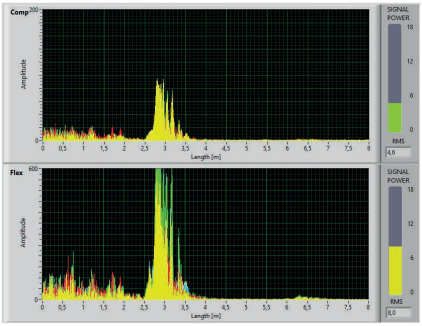
The results for the rebar bolts, presented in Table 3-3 show a good agreement between the results of two instruments. Sixteen of the nineteen bolts obtained the same classification from both instruments or only one step different from the other. In three cases, the RBT and the Boltometer differ two classes or more and only in one case, the bolt TASJ10, the RBT gives a significantly lower classification than the Boltometer. The reasons for the differences between the two instruments will be further discussed in Chapter 4.

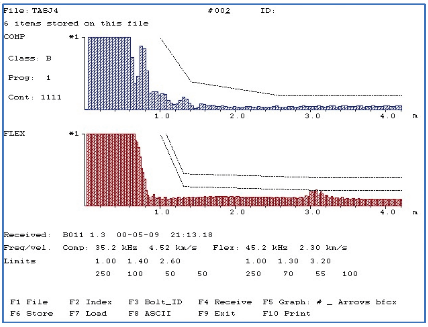
Table 3-3. Comparison between the Boltometer's and the RBT's classification for the production rebar bolts at Äspö HRL.

Bolt	RBT RMS (dB)	RBT * class	Boltometer class
TASJ1	7.2	B	B
TASJ2	0	A	B
TASJ3	3.8	A	A
TASJ4	8	C	B
TASJ5	2.8	A	A
TASJ6	6	B	A
TASJ7	7.8	B	B
TASJ8	2.4	A	B
TASJ9	5.9	A	A
TASJ10	5.4	A	B
TASJ11	6.9	B	C
TASJ12	5.7	A	A
TASP1	10.6	D	B
TASP2	10.3	D	A
TASP3	9.4	C	D
TASP4	9.6	C	A
TASU1	-0.4	A	A
TASU2	-0.2	A	A
TASU3	4.6	A	A

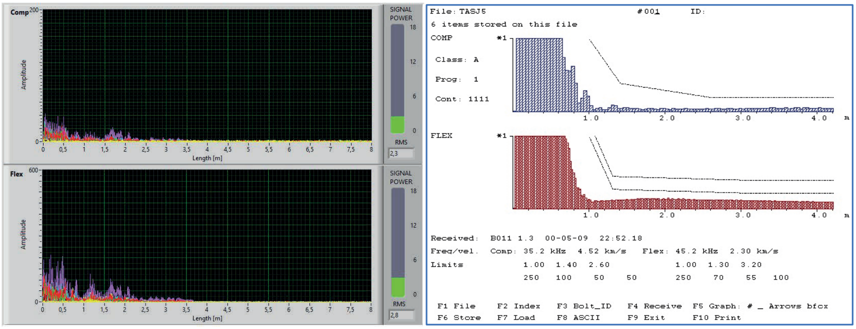
*Classification limits: A= <6, B= 6.0-7.9, C= 8.0-9.9, D= >10

Two example echograms obtained for: the C-rated bolt TASJ4 and the well grouted bolt TASJ5 and are shown in Figure 3-10.





```
File: TASJ4                                #002      ID:
6 items stored on this file
COMP
 Class: B
 Prog:  1
 Cont: 1111

FLEX

Received:  B011 1.3  00-05-09  21:13.18
Freq/vel.  Comp: 35.2 kHz  4.52 km/s  Flex: 45.2 kHz  2.30 km/s
Limits           1.00  1.40  2.60           1.00  1.30  3.20
                 250   100    50    50      250    70    55   100

 F1 File    F2 Index   F3 Bolt_ID   F4 Receive  F5 Graph: # _ Arrows bfcx
 F6 Store   F7 Load    F8 ASCII     F9 Exit     F10 Print
```



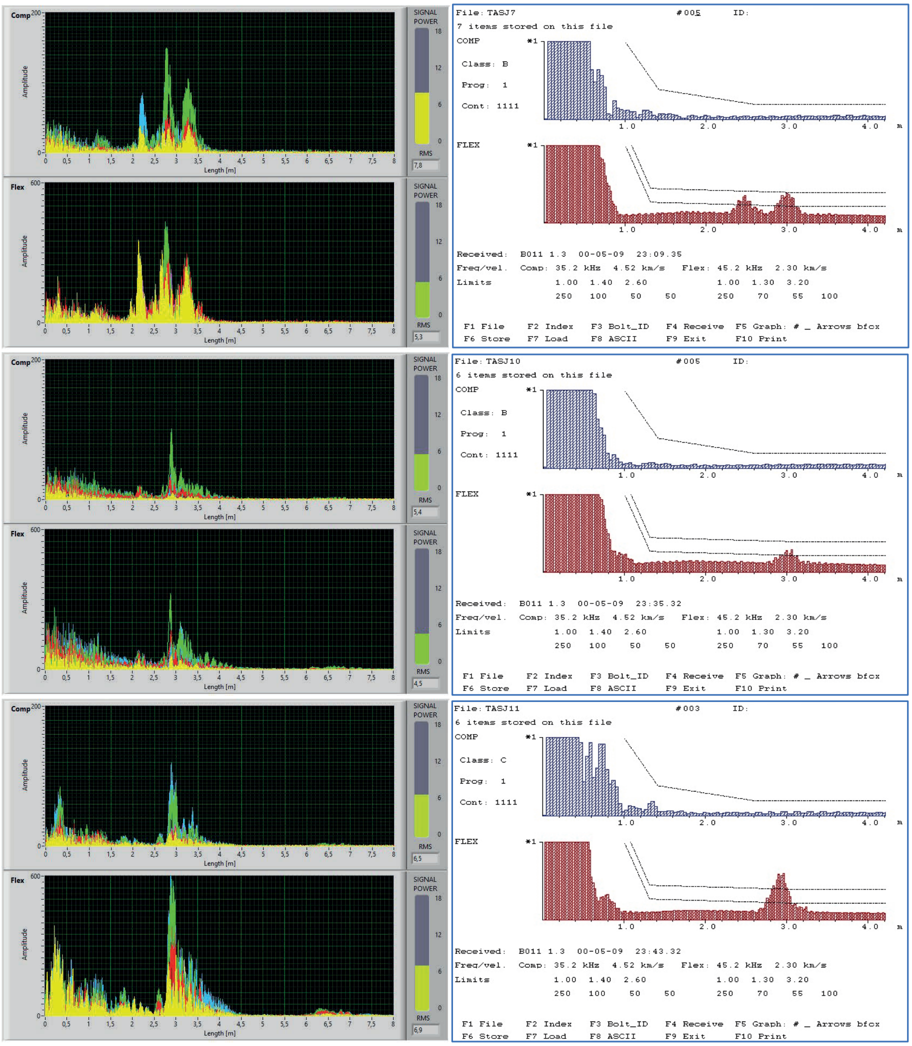
```
File: TASJ5                        #001      ID:
6 items stored on this file
COMP
 Class: A
 Prog:  1
 Cont: 1111
FLEX

Received:  B011 1.3  00-05-09  22:52.18
Freq/vel.  Comp: 35.2 kHz  4.52 km/s   Flex: 45.2 kHz  2.30 km/s
Limits          1.00  1.40  2.60           1.00  1.30  3.20
                250   100    50    50      250    70    55   100

 F1 File    F2 Index    F3 Bolt_ID    F4 Receive    F5 Graph: # _ Arrows bfcx
 F6 Store   F7 Load     F8 ASCII      F9 Exit       F10 Print
```

Figure 3-10. Echograms obtained from the RBT and the Boltometer for the C-rated bolt TASJ4 (upper panel) and the A-rated bolt TASJ5 (lower panel).

3.3 Overcoring

The final verification of the RBT indications would be the destructive inspection after overcoring, to visually inspect the defects indicated by the measurements. For this purpose, ten bolts from the measurements at Äspö HRL (Chapter 3.2.1) were chosen for the overcoring. The idea was to do this in connection with other drilling activities at Äspö, to avoid high costs for the establishment of drilling equipment. Unfortunately, the planned activities were postponed and a full-scale drilling equipment could not be used to that purpose. A small drilling rig with a capacity of about one bolt/week had to be used instead.

In total, three 3m bolts located in the TASJ were overcored with a 10 cm core barrel. Those bolts are referred to TASJ7, TASJ10 and TASJ11, see Table 3.3. The echograms obtained for those bolts are shown in Figure 3-11. It can be seen that all three have distinct end-echoes and somewhat different classifications from the two instruments.



```
File: TASJ7                        #005      ID:
7 items stored on this file
COMP          *1
 Class: B
 Prog:  1
 Cont: 1111
                        1.0        2.0        3.0        4.0   m
FLEX          *1
                        1.0        2.0        3.0        4.0   m

Received:  B011 1.3  00-05-09  23:09.35
Freq/vel.  Comp: 35.2 kHz  4.52 km/s   Flex: 45.2 kHz  2.30 km/s
Limits          1.00  1.40  2.60            1.00  1.30  3.20
                250   100    50    50       250    70    55   100

 F1 File    F2 Index   F3 Bolt_ID   F4 Receive  F5 Graph: # _ Arrows bfcx
 F6 Store   F7 Load    F8 ASCII     F9 Exit     F10 Print
```

```
File: TASJ10                       #005      ID:
6 items stored on this file
COMP          *1
 Class: B
 Prog:  1
 Cont: 1111
                        1.0        2.0        3.0        4.0   m
FLEX          *1
                        1.0        2.0        3.0        4.0   m

Received:  B011 1.3  00-05-09  23:35.32
Freq/vel.  Comp: 35.2 kHz  4.52 km/s   Flex: 45.2 kHz  2.30 km/s
Limits          1.00  1.40  2.60            1.00  1.30  3.20
                250   100    50    50       250    70    55   100

 F1 File    F2 Index   F3 Bolt_ID   F4 Receive  F5 Graph: # _ Arrows bfcx
 F6 Store   F7 Load    F8 ASCII     F9 Exit     F10 Print
```

```
File: TASJ11                       #003      ID:
6 items stored on this file
COMP          *1
 Class: C
 Prog:  1
 Cont: 1111
                        1.0        2.0        3.0        4.0   m
FLEX          *1
                        1.0        2.0        3.0        4.0   m

Received:  B011 1.3  00-05-09  23:43.32
Freq/vel.  Comp: 35.2 kHz  4.52 km/s   Flex: 45.2 kHz  2.30 km/s
Limits          1.00  1.40  2.60            1.00  1.30  3.20
                250   100    50    50       250    70    55   100

 F1 File    F2 Index   F3 Bolt_ID   F4 Receive  F5 Graph: # _ Arrows bfcx
 F6 Store   F7 Load    F8 ASCII     F9 Exit     F10 Print
```

Figure 3-11. Echograms obtained from the RBT (left) and the Boltometer (right) for the overcored bolts TASJ7, TASJ10 and TASJ11 at Äspö HRL.

The overcoring turned out to be very difficult due to large deviations of the bolt holes. The TASJ11 had to be aborted after only approx. 1.5 m since the bolt had been completely cut by the drill bit, while the TASJ10 was stopped after 2.3 m and only for TASJ7 the entire 3m length of the bolt was overcored. Figure 3-12 shows the upper and lower halves of the cores from TASJ7 and TASJ10 with parts of the steel in the rebar bolt visible. First, the cores were cut perpendicularly to the core at length 1.0 m. Since both cores had natural cuts at length approx. 2 m there was no need to cut there. Finally, the cores were split in two halves along the bolt as shown in Figure 3-13.

Figure 3-12. Upper (0-1.5 m) and lower (1.5-3 m) parts of cores from the TASJ7 (upper panel) and the TASJ10 (lower panel).

Figure 3-13. Sawing and splitting of the cores.

Analysis of the cores shows that both bolts seem to be well grouted along almost the entire their length but with one significant defect on each core. The core TASJ7 has a completely unfilled cavity, about 60 mm deep and 50 mm in diameter at 2.3 m length, probably caused by a drilling that has been interrupted for some reason or a neighboring drill hole intersecting, see Figure 3-14. This corresponds very well with the echoes detected in both the RBT and the Boltometer echograms (Figure 3-11).

Figure 3-14. Core from bolt the TASJ7 – a cavity present at the length 2.3 m (left), and a partly filled bolt hole on the opposing core piece (right).

The core from the TASJ10 is well grouted over the 2.3 m that could be analyzed, except for an unfilled air pocket, approx. 400 mm long and 30 mm deep, at the bolt length 0.4–0.8 m, see Figure 3-15. This is a part of the bolt where the echoes may be difficult to interpret, but the RBT measurement shows enhanced echoes in this region. The echo at the end of the bolt could unfortunately not be analyzed due to the deviating bolt hole.

Figure 3-15. Core from bolt TASJ10 – the unfilled pocket, 30 mm deep and 400 mm long at the bolt length 0.4–0.8 m.

The short core from the TASJ11 has a part of approx. 0.5-0.7 m where two natural fractures cut the hole. There is also no grout around the bolt, see Figure 3-16. This coincides well with the high echoes and the RMS values in the RBT measurements. It cannot be excluded, however, that the grout may have been removed during the overcoring. Also in this core, the main defects should be at the end of the core, which unfortunately could not be retrieved.

Figure 3-16. Core from the bolt TASJ11– natural fractures and part of the bolt without grout at 0.5-0.7 m bolt’s length.

4 SUMMARY AND CONCLUSIONS

Development of the RBT was initiated in 2010 as a result of the obvious lack of a modern, easy-handled and robust instrument for non-destructive testing of the grouted of rock bolts. The development has been related to a number of parts of a modern PC based RBT instrument, such as, development of modern analog electronics, integrating the analog/digital module, creating the LabView software, and last but not least, construction of the new piezoelectric probe integrated with permanent magnet. Extensive laboratory tests and a long series of field tests with quite a few prototype instruments were also included in this process. This report shows the results from what is intended to be the final verification, including comparative measurements with the old Boltometer and the overcoring of rock bolts.

The RBT has been based on a PC-concept operating under Windows 10 using an easy-handled touch screen. The instrument, which weighs only a few kg can be comfortably carried by an operator using a specially designed sling. It facilitates faster and more reliable inspections than with the Boltometer.

4.1 Bolt classification

In this report, different classification limits for the RBT have been used for each site, based on different levels of the signal power (RMS) found at the site. These differences may be quite large, e.g. between the RMS values in limestone, like in Dannemora, which are significantly lower than the ones in the Stockholm’s granite. It is therefore vital to install reference bolts, also with predefined defects in different rock environments. The bolt type, borehole diameter, cement grout quality and water-cement ratio should be identical for each reference site.

Both instruments rely on the classification scale A-D, set by the operator, which should be individual for each site; however, the reference measurement is required to obtain relevant classification results using the RBT. For the Boltometer, this scale is in practice a fixed scale, set in advance and, unfortunately, it is seldom adjusted based on local conditions, although this should be done according to the instrument’s manual. The reason is that in most underground projects, there are no reference bolts, and even if there have been installed, the sensitivity of the instrument is too low to really be able to change the classification. Similar scale was chosen for the RBT; however, the classification cannot be performed without a reference measurement. The main reason for that is the fact that the scale is well recognized in the rock building society, and it leaves some freedom in what actions to be taken depending on the total picture from the tests, the bolt grid density, etc.

4.2 Conclusions

The results of the comparative measurements between the Boltometer and the RBT, presented in this report, show that the RBT is more sensitive than the Boltometer to the defects occurring in the grouting. The end echoes are stronger and clearly seen even for the 4 m bolts, which is not the case for the Boltometer. The sensitivity for the echoes from the first meter of the bolt length is also higher. Almost all bolts measured that have been classified as B-D bolts with the Boltometer also showed high echoes at the RBT. The overcoring, even though performed for a limited number of bolts, showed that RBT is sensitive even for small defects in the grouting.

The mining industry and the underground sites with high rock stress are now also using other bolt types, dynamic bolts, which are designed to withstand seismic events and dampen the rock bursts that may occur and still retain the rock from falling down. There is also a need to test old bolts that may have been sheared or weakened by the rock displacement and therefore not carrying any load. This type of bolt has not yet been tested with the RBT and may be the next step in the development of the RBT.

The tests performed on combination bolts, like the PC-bolt and CT-bolts that were installed at Äspö HRL, gives promising results but much more tests are needed to verify the RBT's functionality. This may also be a new application area for the RBT in the near future.

4.3 Recommendations

- Every RBT operator should pass a special training to get basic knowledge in the area of ultrasound, guided waves and RBT instrument operation. Basic knowledge concerning signal processing, especially, the interpretation of ultrasound signals obtained form digital matched filter has to be included in the course.
- The classification limits for the RBT have to be individually chosen for each site and should be based on a reference bolt. To calibrate the RBT it would be highly recommended to use at least two reference bolts: one perfectly grouted and the second provided with an artificial damage in the form of, e.g., 1m long artificial air pocket (covering tube).
- To obtain conformity of the test results using different instruments and probes they should be regularly calibrated.

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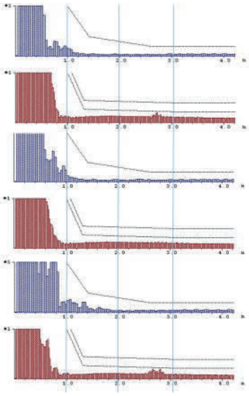
Appendix A – Comparison between the Boltometer and the RBT classification for production rebar bolts at Stockholm Bypass

Bolt no	*dB Comp*	*dB Flex*	*Class Boltometer*	*Class RBT**
1	5.00	14.70	A	D
2	6.20	11.30	A	C
3	9.10	16.20	B	D
4	-0.40	6.00	A	A
5	4.40	15.90	D	D
6	0.70	6.20	A	A
7	6.50	17.60	D	D
8	-0.50	4.30	A	A
9	2.90	9.40	A	B
10	1.90	8.50	A	A
11	8.40	11.70	C	C
12	4.40	12.50	A	C
13	0.70	3.50	A	A
14	2.90	10.90	A	B
15	6.90	15.30	D	D
16	8.70	19.80	C	D
17	0.00	0.00	A	A
18	3.60	7.20	A	A
19	6.00	11.20	D	C
20	0.80	9.60	A	B
21	8.80	14.30	A	D
22	-0.90	1.50	A	A
23	-0.40	0.80	A	A
24	-0.80	-1.10	A	A
25	-0.30	2.80	A	A
26	0.80	6.10	A	A
27	3.10	7.20	A	A
28	0.80	1.10	A	A
29	0.70	3.80	A	A
30	2.00	9.30	A	B
31	5.20	11.00	A	C
32	2.30	8.00	A	A
33	2.90	9.90	A	B
34	9.00	6.80	A	B
35	1.90	9.40	A	B
36	-0.80	1.80	A	A

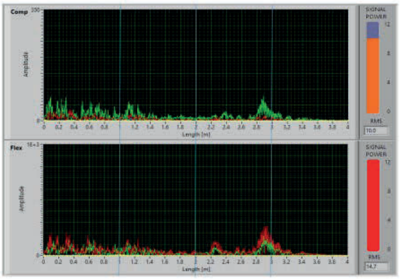
37	-0.90	5.20	A	A
38	-0.50	4.50	A	A
39	-1.10	4.50	A	A
40	3.10	10.30	A	B
41	1.60	6.10	A	A

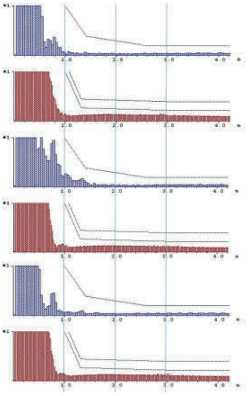
*Classification: A= <9, B= 9.0-10.9, C=11.0-12.9, D= >13.

Appendix B – Echograms showing Boltometer and the RBT results for production rebar bolts at Stockholm Bypass.

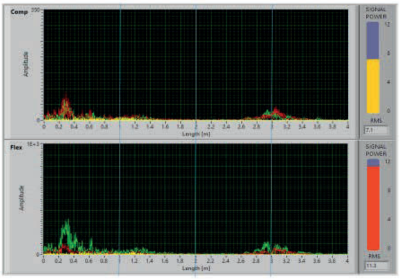


Bolt 1

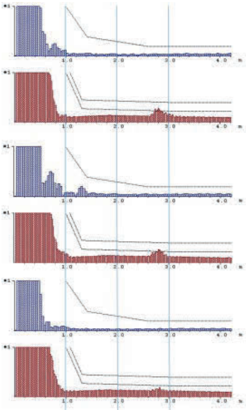


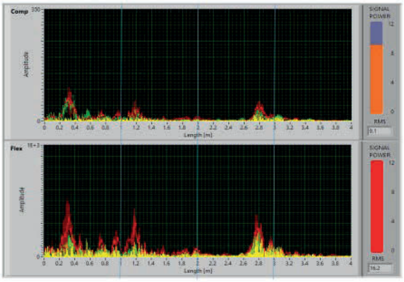


Bolt 2



Bolt 3





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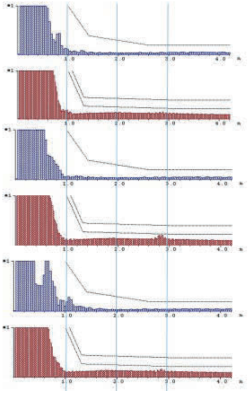

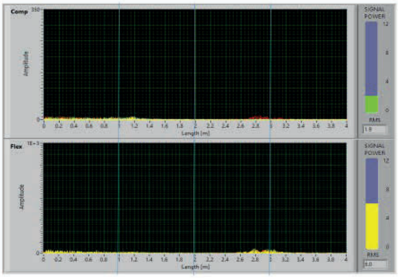

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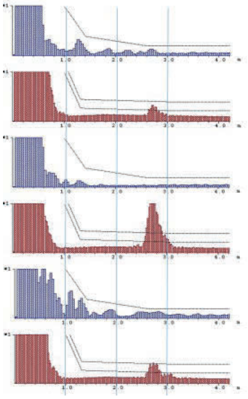

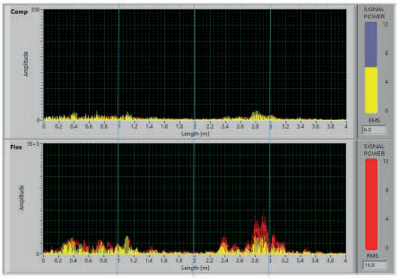

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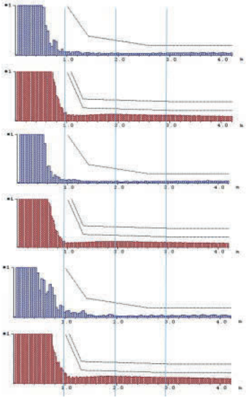

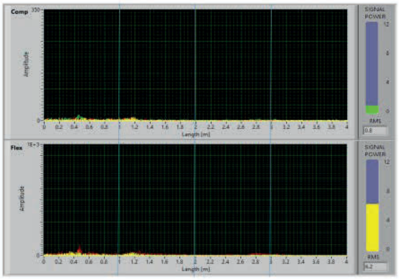

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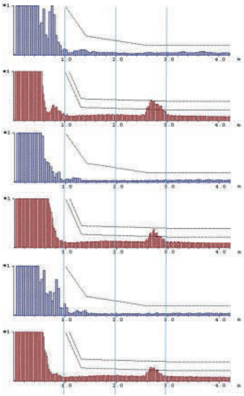

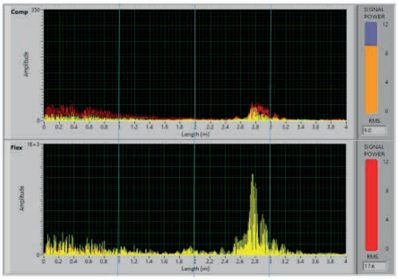

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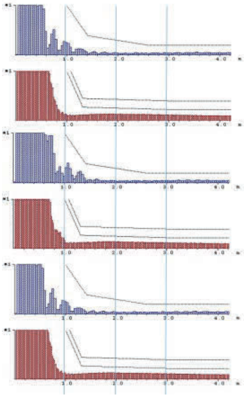

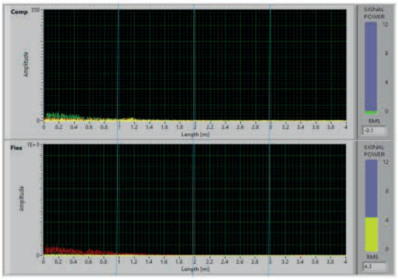

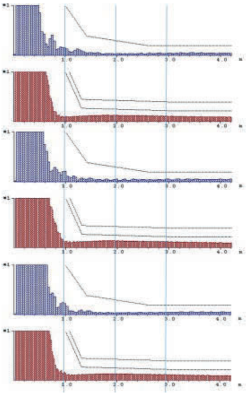

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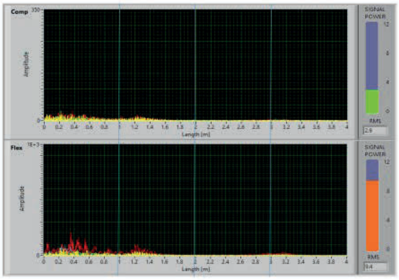
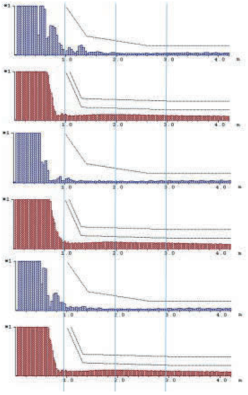
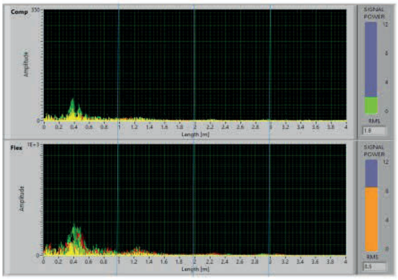
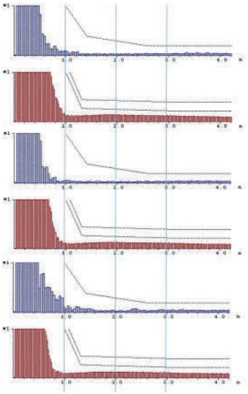


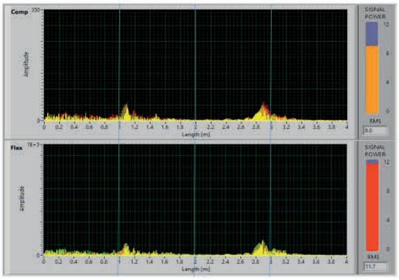


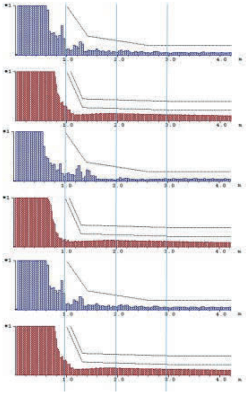
Bolt 10





Bolt 11





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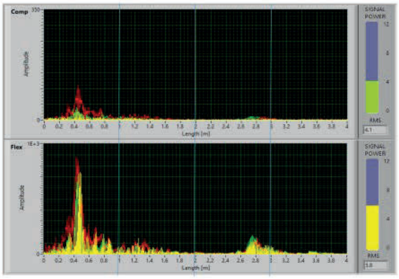

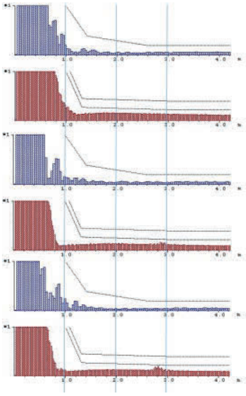

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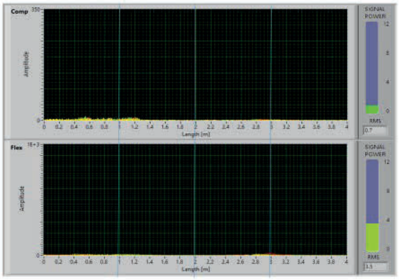

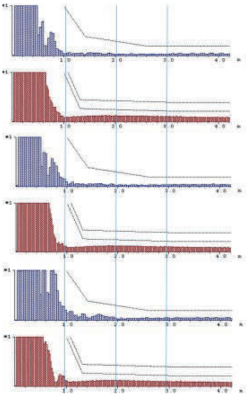

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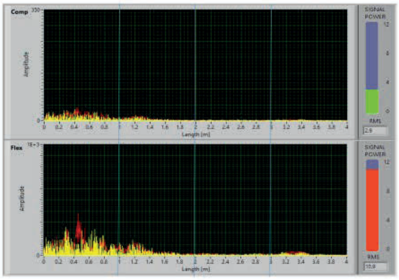

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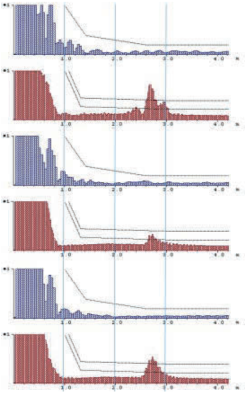

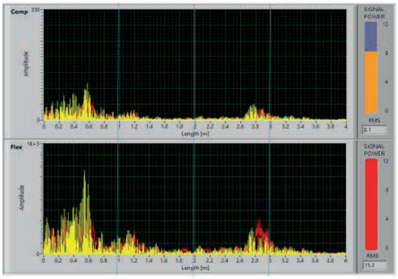

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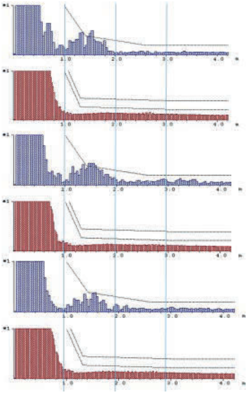

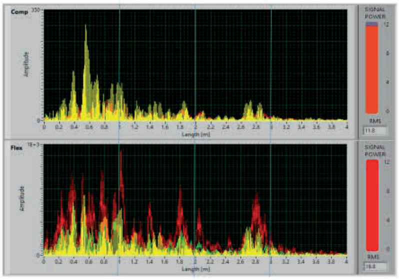

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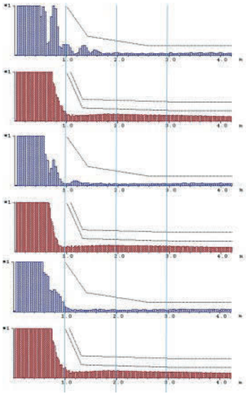

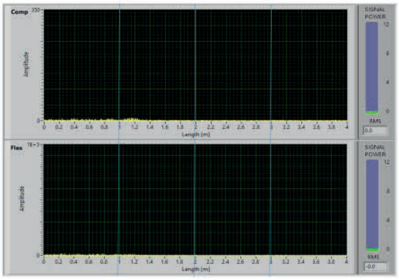

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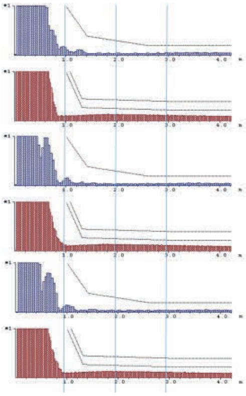

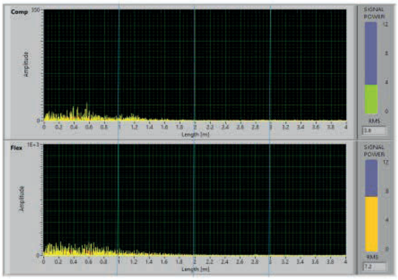

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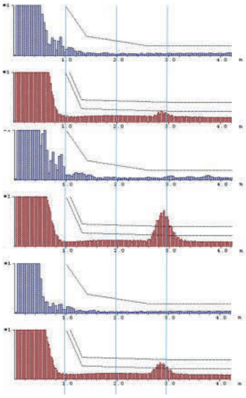

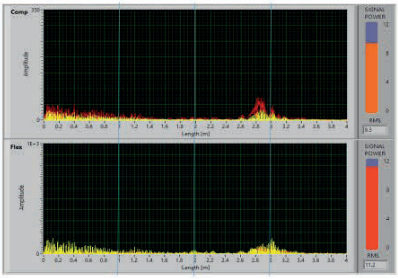

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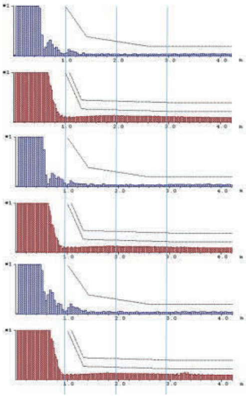

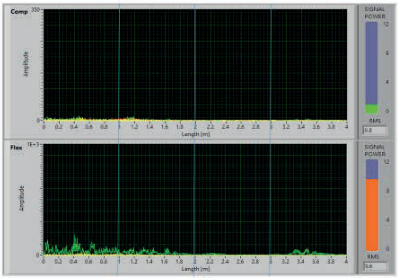

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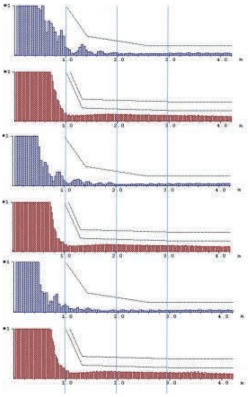

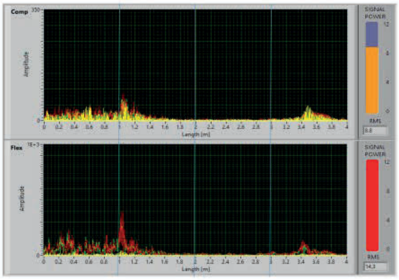

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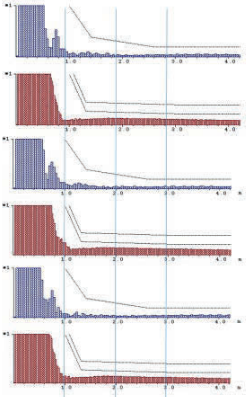

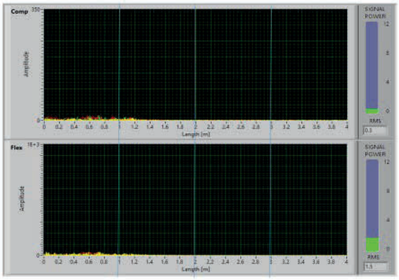

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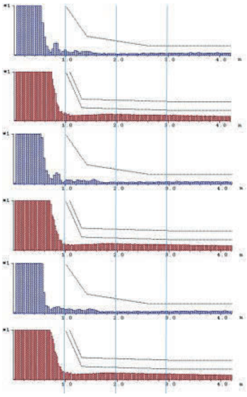

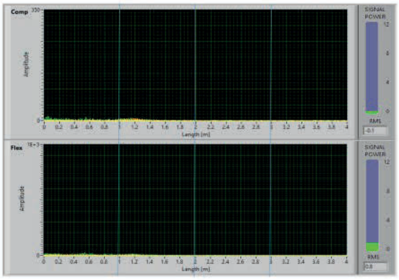

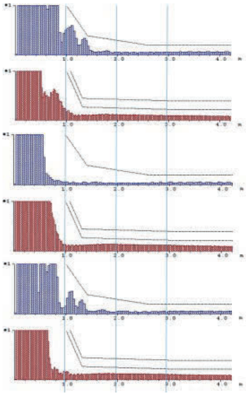

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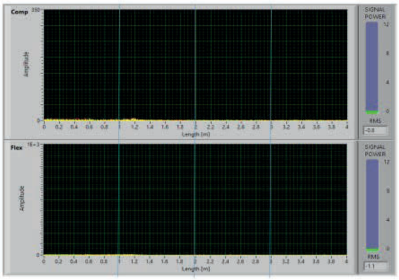

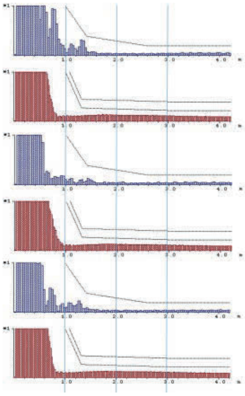

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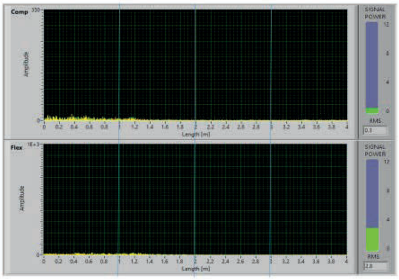
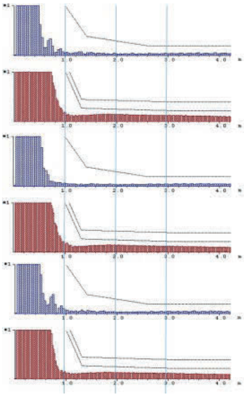
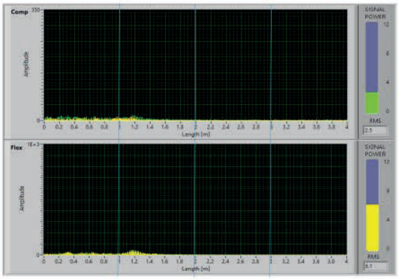
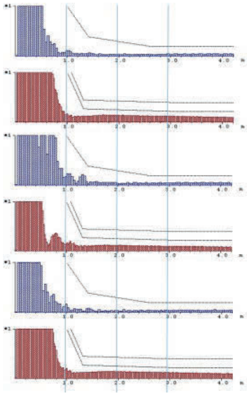


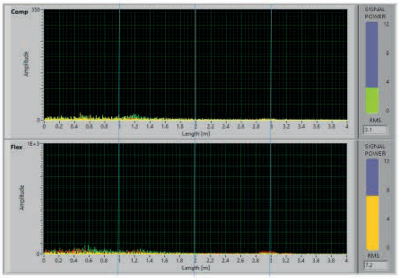


Bolt 26

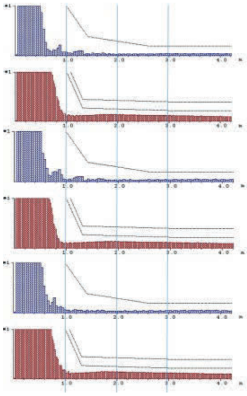


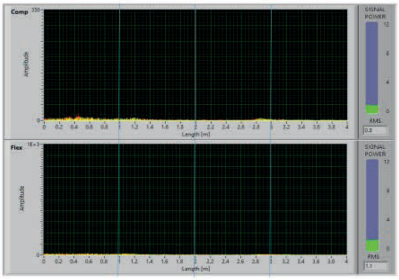
Bolt 27





Bolt 28





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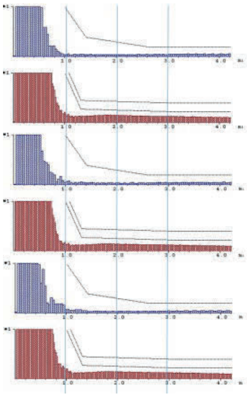
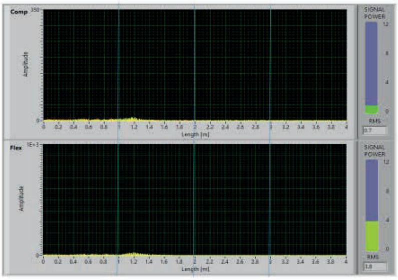
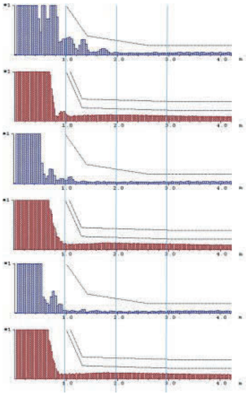
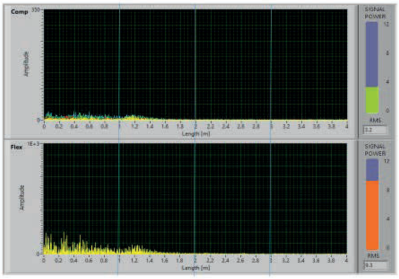
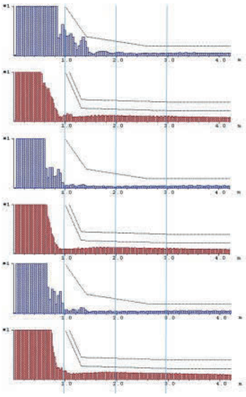






Bolt 30





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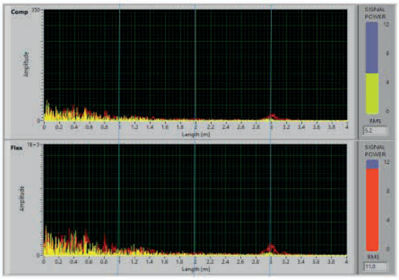

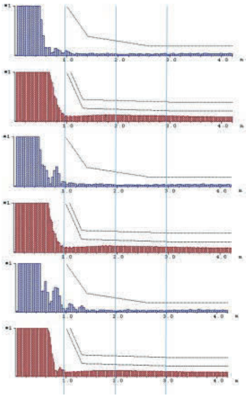

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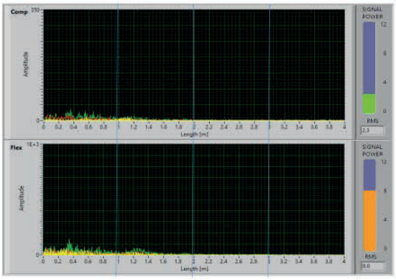

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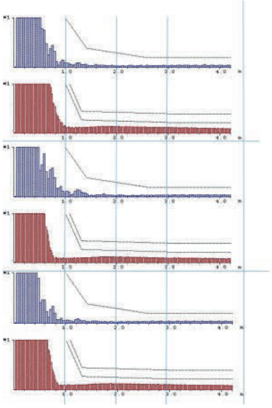
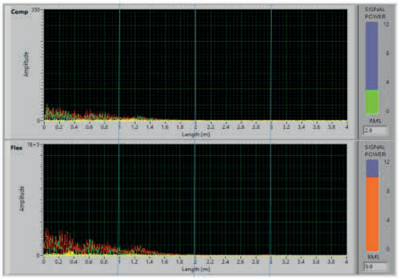
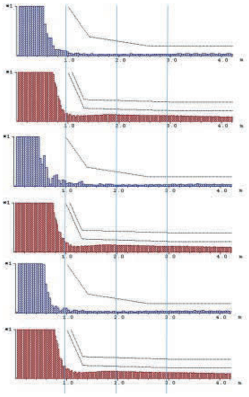
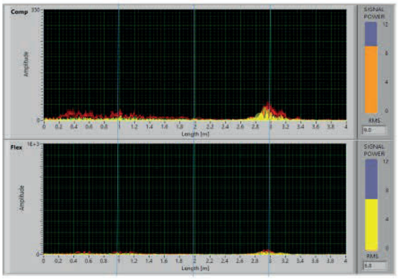


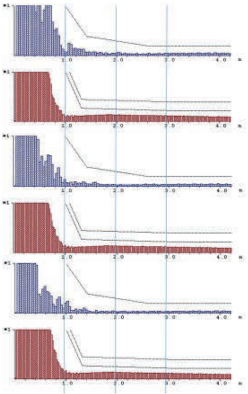


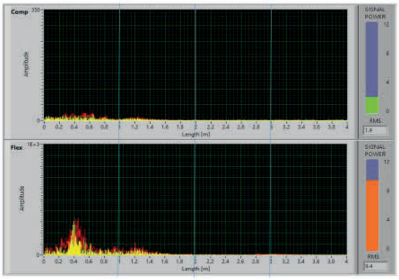
Bolt 34



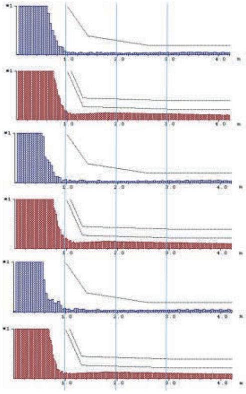


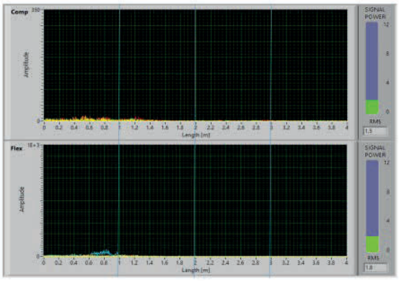
Bolt 35





Bolt 36





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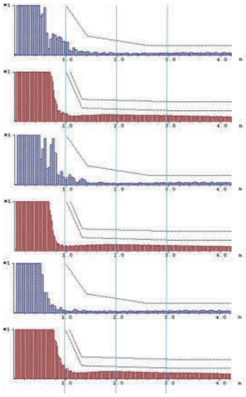

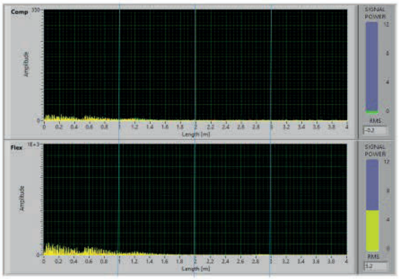

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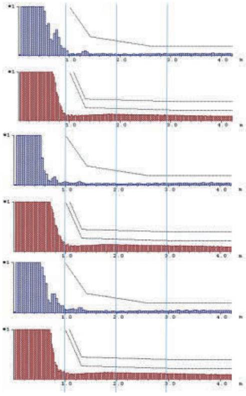
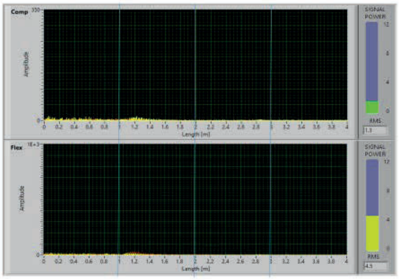
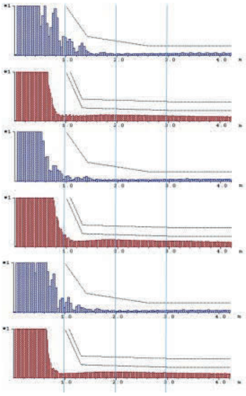
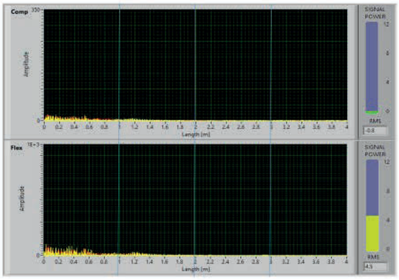
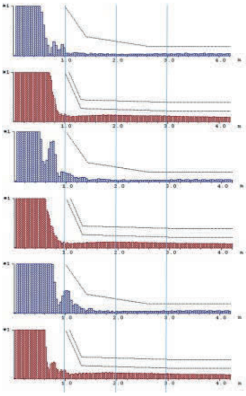




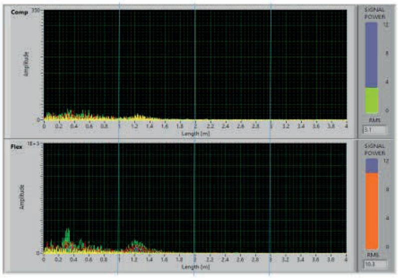


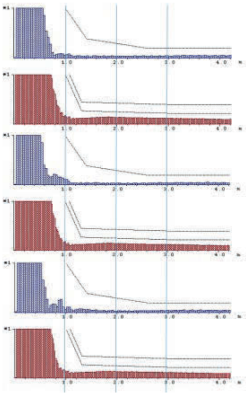
Bolt 39



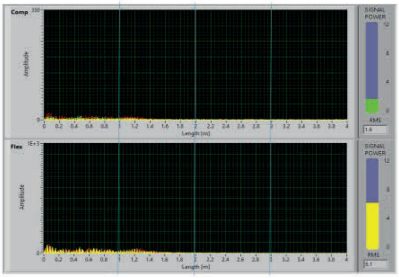


Bolt 40





Bolt 41



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