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Improving rockbolt design through comparative laboratory and in situ testing: the success story of the Super MDX bolt

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Abstract

The underground mining ground support landscape is constantly requiring product improvements, whether to support higher loads, provide higher dynamic performance or improve process efficiencies. When developing new dynamic ground support products, design validation plays a critical role in substantiating new concepts and design calculations.

Design validations range from laboratory component and assembly testing to more complex in situ testing in the end-users' ground conditions. These different types of testing provide a stepwise process to improve product performance characteristics in controlled settings before larger investments in time, personnel and machinery are required.

This paper compares and presents the test results from laboratory component testing, laboratory assembly testing and in situ assembly testing on Sandvik's newly developed Super MDX bolt, which has been developed to increase the range of application for the hybrid friction-mechanical MDX bolt range.

Keywords: *ground support, laboratory testing, in situ testing, product development, dynamic ground support, friction-mechanical bolts*

1 Introduction

The development of new ground support products and technologies requires a thorough understanding of the operating environment and how new products will interact with the existing machinery and the target rock mass. Whether designing excavation tools, machinery, material handling equipment or ground support systems, accurate characterisation of the requirements of the end use environment is essential to optimise performance, reliability, and safety. In this case, for ground support design, and more specifically rockbolt design, transitioning from the design process and laboratory testing to in situ trials can present some challenges. These challenges can range from how laboratory testing boundary conditions relate to the underground environment to the variations in installation and test methods.

In recent years, there has been increasing interest in the use of in situ testing methods to complement conventional laboratory investigations. Field-based testing offers the advantage of capturing the influence of geological variability, structural discontinuities, installation practices, moisture content, and scale effects that can significantly influence product performance (Hoek & Brown 1997). These influences can change the performance of new products, particularly when laboratory testing methods and boundary conditions do not correlate closely with expected field conditions.

Design validation of new ground support products typically involves a stepped assessment combining laboratory testing, numerical analysis, and in situ trials to demonstrate product performance and structural capacity (Tshitema & Kallon 2021). Initial validation is commonly undertaken using controlled laboratory testing to quantify performance parameters such as static load capacity, anchor mechanism performance, bolt failure modes and dynamic performance. As laboratory testing cannot fully reproduce the complexity of

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in situ rock mass conditions, field-scale validation is conducted in mining environments to evaluate installation suitability, interaction with installation methods and machinery, and performance under mining-induced loading methods. The combination of laboratory testing and in situ trials provides a rounded method for validating product performance, confirming design assumptions, and reducing technical risk prior to large-scale product trials within mining operations.

2 The Super MDX bolt

Since the launch of the MDX bolt in 2017 (Darlington et al. 2018), a significant catalogue of knowledge and test results has been acquired for both laboratory and in situ testing (Vallati et al. 2022; Darlington et al. 2019). The MDX bolt has been shown to perform consistently across a wide range of ground conditions under both static and dynamic loading. Through extensive testing of the MDX bolts in both laboratory and in situ conditions, several areas have been identified to allow further improvement to the performance of the MDX bolt range; particularly, increased tensile capacity, increased dynamic capacity, additional wedge expansion and rock face compression.

The MDX bolt has shown that when the wedges are securely anchored in the rock, the bar can reach the ultimate load of 225–250 kN during an in situ static test. When subjected to in situ dynamic testing, the MDX can dissipate an impact energy up to 44.1 kJ without bar failure. However, several requests have been received for a bolt that is stronger in both static and dynamic performance.

The Super MDX (SMDX) bolt has addressed these points to increase the applicable use of the MDX bolt range, with a new bar to increase static and dynamic performance, redesigned wedge mechanism, and a system to allow for rock face compression during bolt installation. The central bar is a 20 mm round bar (compared to a 20 mm ribbed bar for the MDX), which has been designed to increase both the static and dynamic capacity of the SMDX, with a static capacity of 270 kN and dynamic capacity of up to 47.1 kJ (dissipated input energy in a single impact without bar failure). The bar also has a paddle at the nut end to interact with a new internal tube bridge and prevent bar ejection during a shear event or when the bar is overloaded.

The wedge mechanism has been redesigned to increase the possible expansion up to 68 mm, which is achieved using a 2-stage wedge system. This wedge system has the potential for applications in a wider variety of ground conditions, from very good to very poor and potentially in paste applications. The wedge end of the bar now includes a percussion washer, which, in conjunction with a gap between the radiused washer and tube, transfers the percussive forces from the installation tool to the bar and into the welded wedges. This then acts to drag the bolt into the borehole, rather than pushing, which is the case when the percussive forces are applied to the nut end of the tube. This change in percussive energy transfer can greatly reduce the risk of bolt buckling during installation and has the potential to decrease the installation time of the SMDX bolt. Additionally, this change has allowed a reduction in the tube material thickness, resulting in a weight of 11.5 kg for a 2.4 m bolt, a reduction of 0.8 kg when compared to an MDX bolt. The design features of the SMDX are shown in Figure 1.

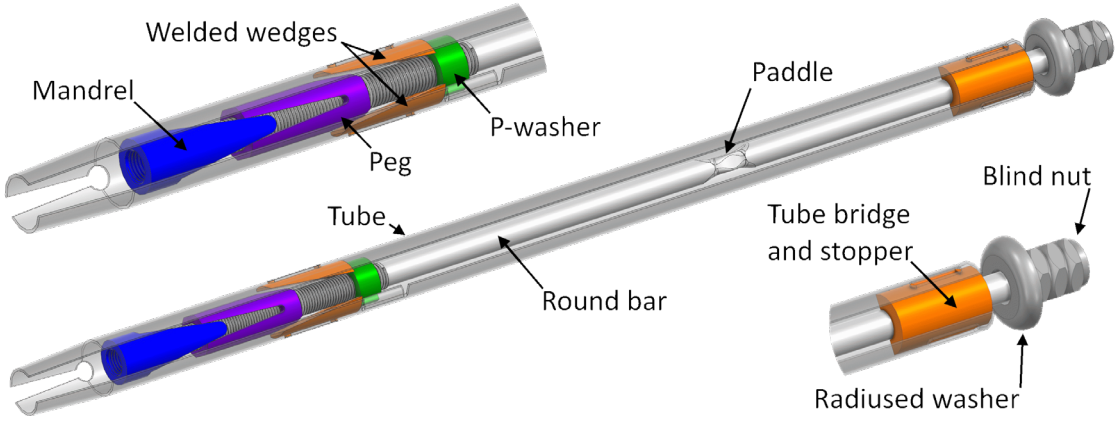


Figure 1 Super MDX features

The SMDX bolt is installed using the same machinery, tools and method as the MD and MDX bolts; percussive installation into a pre-drilled borehole, using a Ø43–45 mm drill bit, followed by left-hand rotation to a design torque of 350–450 Nm. The SMDX bar has been designed to withstand installation torques up to 650 Nm, which is the upper range of torque output for the new Sandvik rock drills.

These new design features and Sandvik's wide range of dynamic testing apparatus and methods, provide an excellent opportunity to compare the performance of the new SMDX bolt under 3 conditions: laboratory component testing, laboratory bolt testing and in situ bolt testing.

3 Laboratory testing

In order to quantify the improvements of the SMDX bolt, significant testing was conducted under laboratory component testing conditions, which was conducted at the Sandvik research and development facility located in Heatherbrae, New South Wales, Australia. This laboratory component testing was focused on the performance of the new bar, including full-length bar tensile testing and full-length bar dynamic testing.

The full bar quasi-static testing is performed to determine the performance of the bar in the as-used condition, taking into account any strength reductions induced by manufacturing processes applied to the bar. The bar quasi-static performance is shown in Table 1 and Figure 2, where the samples showed an average yield load of 227 kN, an average peak ultimate strength of 281 kN and an average bar elongation at failure of 154 mm.

Table 1 Super MDX full-length bar tensile testing results

Sample	Yield load (kN)	Peak load (ultimate load) (kN)	Elongation at failure (mm)	Failure location
S-1	226	279	146	Bar centre
S-2	228	281	154	Bar centre
S-3	227	282	148	Bar centre
S-4	226	282	167	Bar centre
AVERAGE	227	281	154	
MDX bolt	191	244	190	Wedge thread

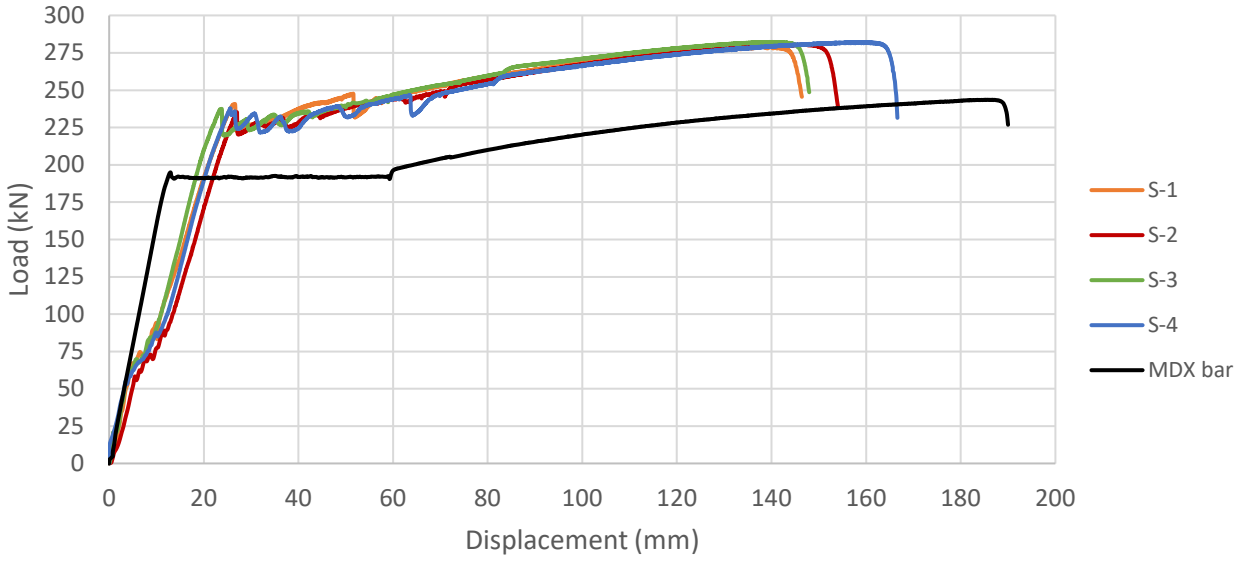


Figure 2 Super MDX full-length bar tensile test results

When comparing these results with the existing MDX bar, the SMDX bar shows a clear increase in both yield strength and ultimate strength, but a decrease in bar elongation at failure. Another very important observation to make is the MDX bar failure typically occurs in the wedge thread (furthest from the blind nut), but this is not a design guarantee, and failure can occur anywhere along the bar. In contrast, the SMDX has been designed to guarantee failure in the central portion of the bar. This is crucial for the operation of the new stopper system, which relies on the bar remaining intact between the paddle and the blind nut. On all samples that were tested to destruction (in both static and dynamic configurations), the bar failed in this central portion, as intended.

The component dynamic testing was conducted using the Sandvik ground support component dynamic test rig. This test rig utilised the free-fall of mass technique to apply a dynamic impulse to the test sample, where the test sample serves as the guide for the drop mass (Darlington et al. 2022). The test apparatus uses a piezoelectric shock sensor to measure the load applied to the test sample (located at the bottom of the test sample), and a video-based displacement monitoring system to track the motion of the bottom of the test sample. The test rig has a capacity to apply an impact energy up to 68 kJ in a single impact, which is controlled by changing the drop height or drop mass. This test rig is critical in the development of new bar materials for dynamic products, where samples can be tested with desired boundary conditions, providing quick and repeatable test results. The components of the laboratory dynamic test apparatus are shown in Figure 3.

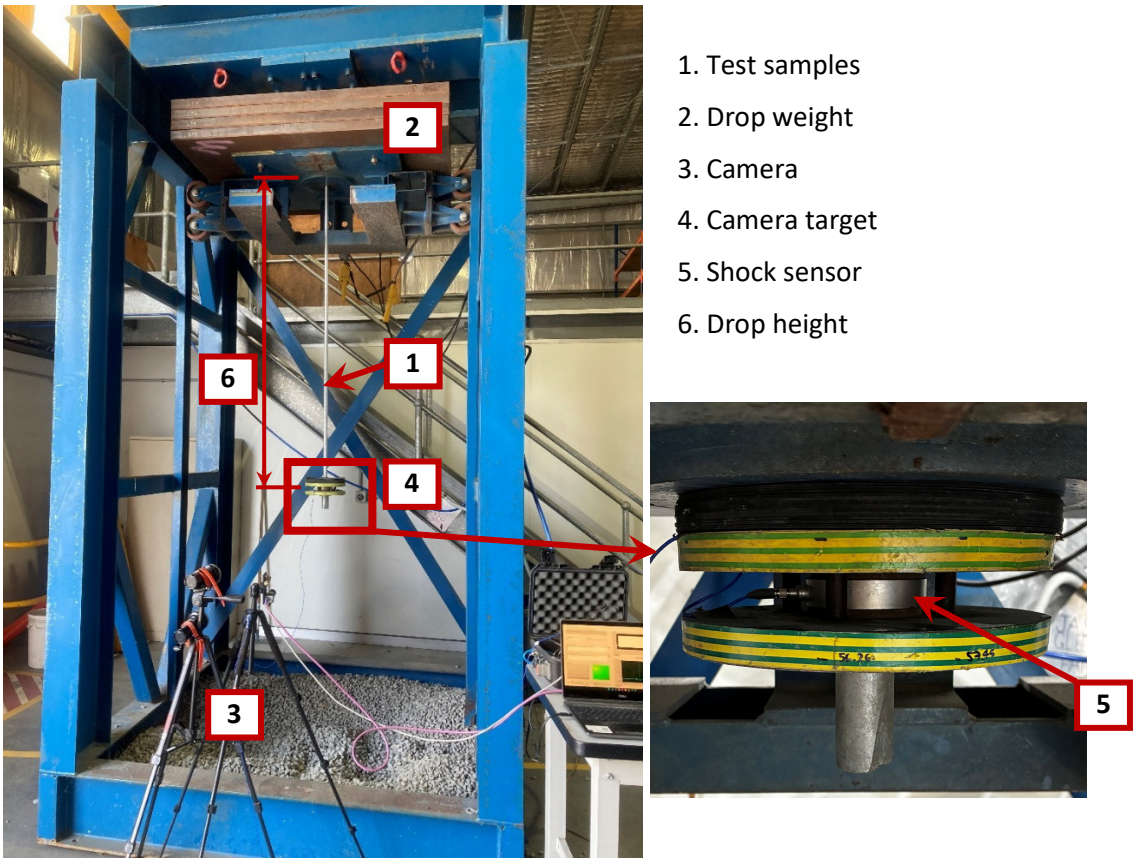


Figure 3 Laboratory component dynamic test apparatus

Dynamic testing using any test apparatus, unfortunately, only provides a single energy data point, where the desired impact energy is selected prior to testing. Whereas a quasi-static test allows sample testing gradually to destruction, dynamic testing can only test to the selected impact energy, which can cause destruction when selected correctly. Therefore, selection of the impact energy is as important as the testing itself, particularly if a limited sample set is available. For the SMDX testing regime, the impact energy was selected at the estimated bar energy capacity 45.5–46.0 kJ.

The test results for the laboratory component dynamic testing are show in Table 2 and the dynamic response is shown Figure 4.

Table 2 Lab component dynamic testing results

Sample	Theoretical impact velocity (m/s)	Theoretical impact[1] energy (kJ)	Peak load (kN)	Average impact load (AIL)[2] (kN)	Absorbed energy (kJ)	Peak system displacement (mm)	Final system displacement[3] (mm)
D-1	5.8	45.8	235	213	40.2	188.6	Bar failure (162 [4])
D-2	5.8	45.6	244	227	42.8	188.3	Bar failure (163 [4])
D-3	5.8	45.9	243	230	43.5	188.9	165
D-4	5.8	45.7	239	229	43.6	190.5	162

1. Theoretical impact energy is the potential energy at the point the drop mass impact the test plate; 2. AIL = Absorbed Energy/peak displacement; 3. Measured on bar after test; 4. Estimate from recorded displacement data

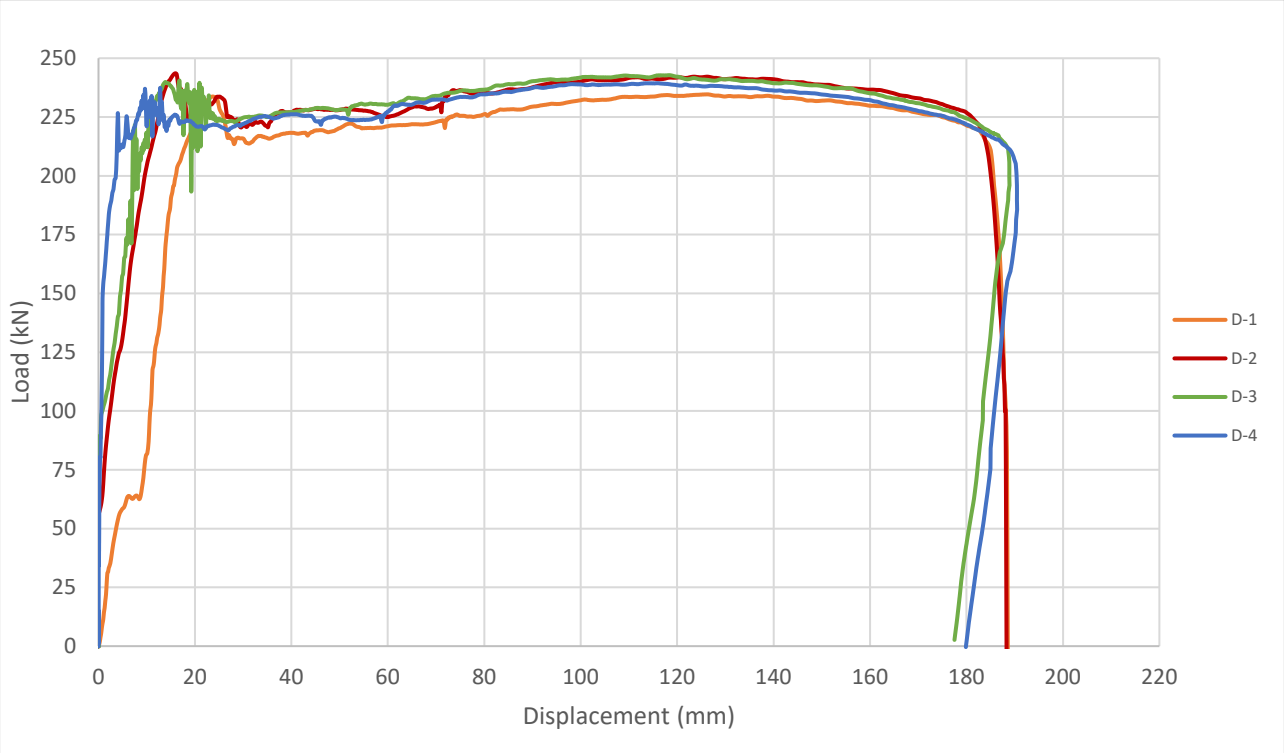


Figure 4 Lab component dynamic testing response

Upon the completion of this component testing, with the positive test results achieved, assembly laboratory testing was conducted. This type of testing provides an insight into the expected performance of the completed product when used in situ but is performed under laboratory conditions. SMDX bolt samples were subjected to 3 types of laboratory assembly testing: installation using the Sandvik bolt installation test stand 'BIT', assembly 'push' testing in the BIT and assembly dynamic testing in the Sandvik ground support laboratory dynamic test rig.

The Sandvik (BIT) utilises a Sandvik HLX5 rockdrill, fitted to a jumbo feed rail, to provide percussive installation conditions. These installations provide initial feedback on the durability of new designs when subjected to percussion and feed forces experienced in the underground environment, without the need to arrange underground trials. The BIT has also been configured to conduct 'push' testing, which loads the bolt anchor in a quasi-static condition.

SMDX samples were installed into pre-cast concrete blocks, pre-drilled with a Ø44.5 mm drill bit, using the standard MDX bolt installation procedure. Samples were then 'push' tested to assess the assembled bolt performance during percussive installation and laboratory quasi-static load capacity. The BIT 'push' testing configuration is shown in Figure 5 and involves 'pushing' the front block away from the anchor block using four hydraulic cylinders.

During BIT 'push' testing, several key positions are measured: the relative position between the front block and anchor block, the position of the bar end relative to the end of the anchor block and the position of the flat washer relative to the front of the front block, as shown in Figure 5. These measurements can identify the quality of the wedge system to secure the tube within the anchor block, along with the method of bolt elongation; whether that be through wedge movement, bar stretch or washer/plate compression.

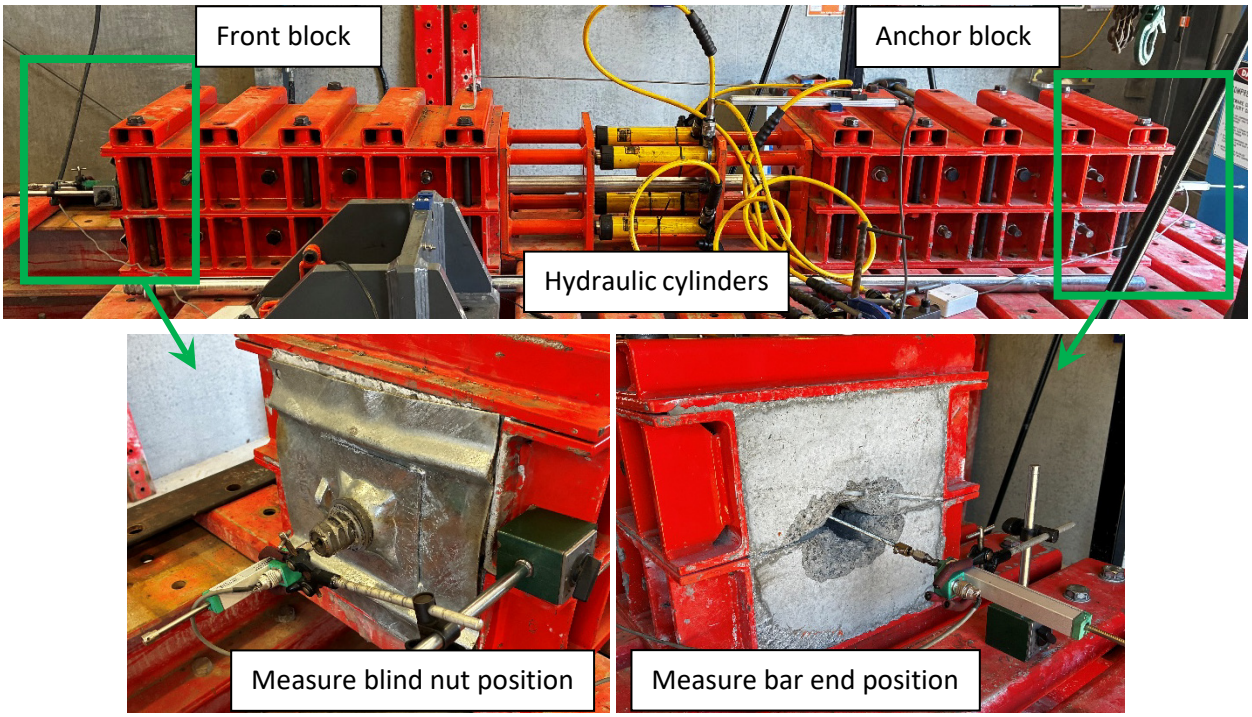


Figure 5 BIT 'push' test configuration

The installation of the SMDX samples with the BIT demonstrated the effectiveness of the percussion washer to 'drag' the bolt into the borehole, where installation timing was similar to the MDX bolt. The number of rotations of the SMDX bar was higher than the MDX bolt, which was as expected with a 3-part wedge system, but the stall torque of the rotation motor (400 Nm) was successfully reached.

When performing the 'push' test, the bolts were loaded to the ultimate load of the bolt and plate system or the end of system stroke, which in this case was the end of the system stroke. At this point of the test, no items were overloaded, where the test was stopped at a total block separation of 196 mm, of which 50 mm was wedge engagement to the yield point of the bar, further increasing the strength of the bolt anchor. The remaining 146 mm was a combination of further wedge elongation, bar elongation, plate compression and tube stretch, as shown in Figure 6.

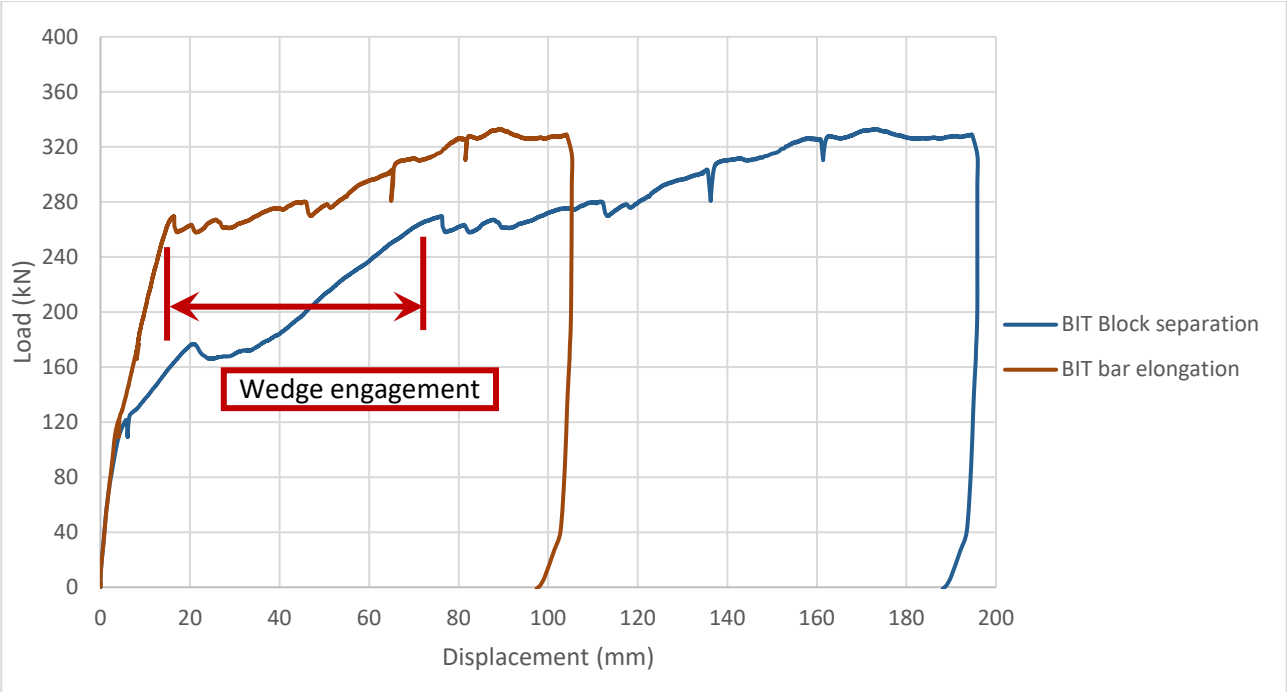


Figure 6 BIT 'push' test results

The concrete blocks of the BIT can be disassembled after installation and 'push' testing to easily assess the final condition of the sample. When inspecting the SMDX bolts after installation and 'push' testing (Figure 7), the wedge system showed good performance, where the mandrel pulled fully into the peg, then pulled into the welded wedges to create a large anchor (approximately Ø63.1 mm), demonstrating excellent performance of the new 3-part wedge system when installed into a Ø44.5 mm borehole. Another indication of the strength of this wedge system can be seen in the level of spalling occurring around the wedge area, which is a consequence of the large expansion forces from the SMDX 3-part wedge system.

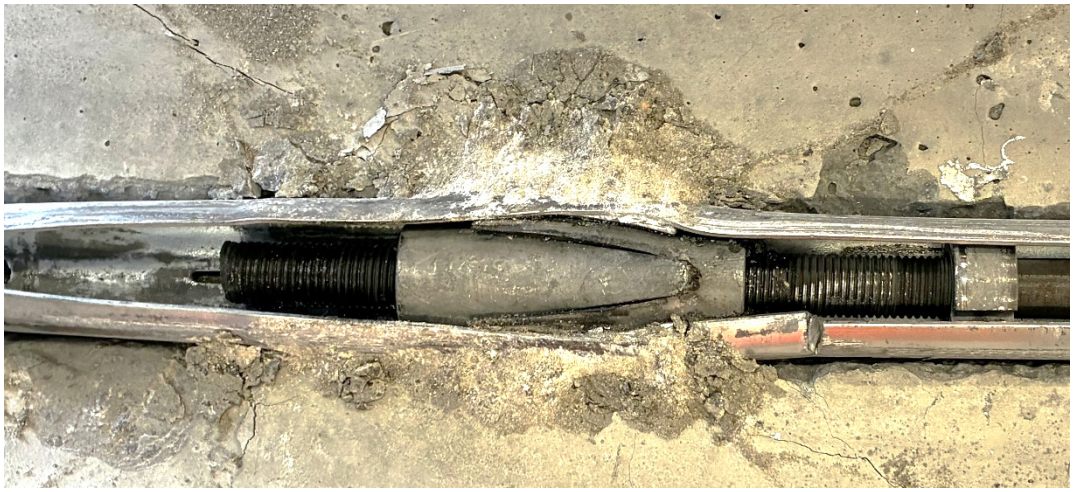


Figure 7 Condition of Super MDX wedge system after BIT 'push' test

The SMDX introduces a new ejection stopper design, whereby the tube bridge is an internal fixture which interacts with a paddle pressed into the bar to capture the ejecting bar. To test the functionality of this new system, several samples were prepared and tested to ultimate bar load. The tube was secured to the test frame to simulate the tube anchored within the borehole, and total bar ejection was recorded. In all test samples, the bar was successfully stopped by the ejection stopper, where the paddle caught on the tube bridge, demonstrating a very effective stopper system. Two such test samples are shown in Figure 8, with a maximum ejection distance of 265 mm.

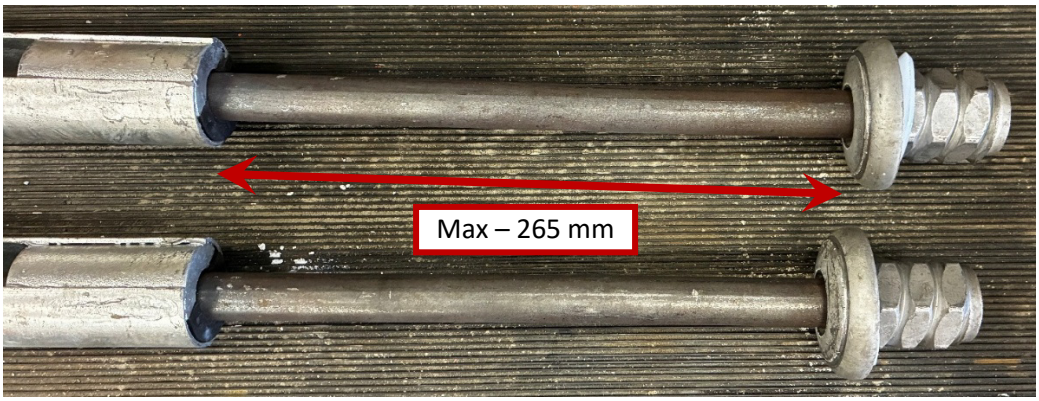


Figure 8 Super MDX ejection performance

Assembly laboratory dynamic testing was conducted using the Sandvik dynamic test apparatus, located in Heatherbrae NSW. This test rig utilises the momentum transfer method and modifies the impact energy by changing the drop height. The load response is recorded using a load cell array and displacement is captured using a high-speed digital camera and image processor (Evans 2024). Due to sample and time constraints, only 2 samples were tested with potential energy input of 63.6 and 56.6 kJ, resulting in one overload and one stable result, as shown in Table 3 and Figure 9.

Table 3 Lab assembly dynamic testing results

Sample	Theoretical impact velocity (m/s)	Theoretical impact[1] energy (kJ)	Peak load (kN)	Average impact load (AIL)[2] (kN)	Absorbed energy (kJ)	Peak system displacement (mm)	Final system displacement[3] (mm)
LD-1	7.4	63.6	297.8	180.2	46.6 [4]	206.5 [4]	Bar failure (206.5[4])
LD-2	7.0	56.6	324.3	277.8	46.6	175.9	165

1. Theoretical impact energy is the potential energy at the point the assembly impacts the sand bed; 2. AIL = Absorbed Energy/peak displacement; 3. Measured on bar after test; 4. Recorded at the point of overload

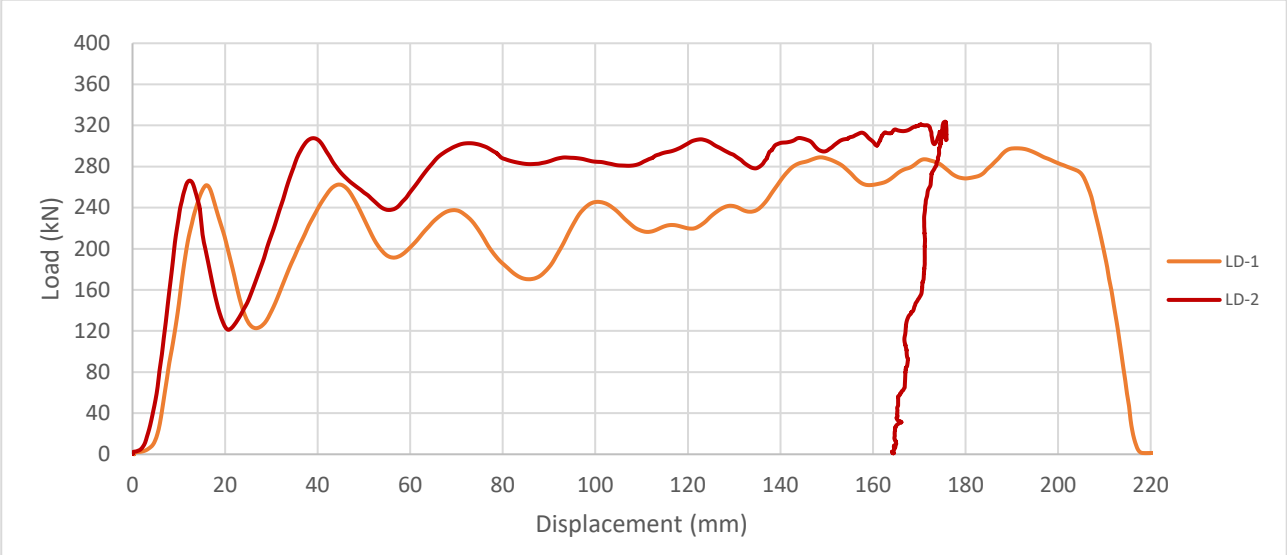


Figure 9 Lab assembly dynamic testing response

Sample LD-1 failed through overload of the plate/washer interface at a displacement of 193 mm; however, it still showed good performance up to the point of overload. Sample LD-2, with a slightly lower drop height

(hence lower input energy), successfully dissipated the dynamic energy without bar failure (a stable result). After the product launch, further testing will be performed to more precisely identify the input energy that just causes bolt overload, and to achieve a larger sample dataset to better understand the bolt behaviour at these higher dynamic energies.

4 In situ testing

In situ assembly testing was conducted at the Sandvik test mine in Tampere, Finland, which provides an underground environment with somewhat controlled conditions. This testing was conducted to determine the applicability of the final SMDX design when installed with underground machinery (DD420 Jumbo) and subjected to in situ static and dynamic testing.

The trial was conducted in the C1.6.2 drive, which had recently been developed. The drive dimensions were approximately 8 m wide and 6–6.5 m tall. The dynamic test bolts were installed in the backs between 14 to 20 m from the end of the drive, and the static testing bolts were installed in the lower wall 40 m further down the drive. The drive is developed in competent Granodiorite with uniaxial compressive strength (UCS) ranging from 130 to 142 MPa.

The in situ tests conducted included an installation trial, in situ dynamic testing using the Sandvik in situ dynamic test rig (DTR002) to apply dynamic energy to the bolts, and in situ quasi-static testing, replicating static loading of the bolt. All testing was conducted by the Sandvik ground support research and development team using calibrated test equipment.

The installation test involved closely monitoring both the machine performance indicators and bolt visual performance during the installation of a series of test bolts. During this trial, the machine performed as expected, and the installation performance did not vary from existing MDX bolt, with installation times ranging from 19–30 seconds, compared to 18–29 seconds for the MDX bolt. Operator feedback was that there was no noticeable difference between installing the MDX and SMDX bolts, other than a slightly reduced bolt weight for the SMDX.

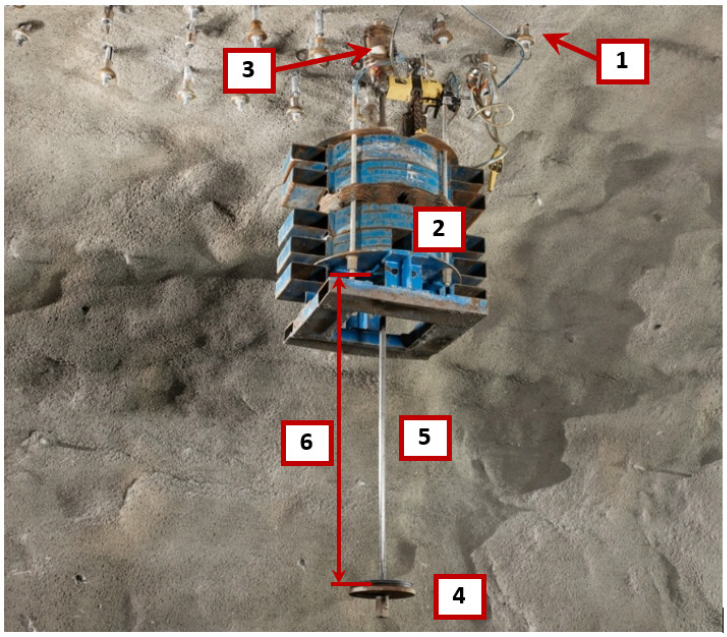
The dynamic test was conducted using Sandvik dynamic test rig (DTR002), which utilises the free-fall of mass energy transfer technique. However, as the test bolts are completely installed into the rock mass, a drop rod must be used to guide the test mass and transfer the kinetic energy from the bottom load nut to the test bolt. This drop rod is connected to the test sample through a specially designed set of claws, which house the shock sensor, recording the load applied to the test sample, and the accelerometer, recording the acceleration of the bolt, which then is used to calculate the displacement of the test sample. These claws also allow testing of bolts that are installed at a slight angle to vertical (up to 7°) without damaging the test bolt or sensors. To connect the claws to the test sample, bolts are installed with a specially designed domed collar, as illustrated in Figure 10. Additionally, a support bolt is installed adjacent to the test bolt to allow connection of a pneumatic chain hoist which allows management of the drop mass.



(a) (b)

Figure 10 (a) Test sample with domed collar; (b) Support bolt with hoist collar

The dynamic energy is controlled by modifying the drop mass and drop height, with a maximum input energy capacity of 63 kJ. The in situ dynamic test rig components are shown in Figure 11.



1. Test sample
2. Drop weight
3. Claws
4. Bottom load nut
5. Drop rod
6. Drop height

Figure 11 DTR002 configuration

The in situ dynamic testing regime installed twelve samples, where 10 samples were subjected to single impact dynamic testing. The goal was to identify the maximum input energy the bolt could dissipate without failure, where the results are shown in Table 4 and the energy response is shown in Figure 12.

Table 4 In situ dynamic testing results

Bolt number	Loading mass (kg)	Drop height (mm)	Theoretical impact velocity (m/s)	Theoretical input energy[1] (kJ)	Peak load (kN)	Average impact load (AIL)[2] (kN)	Energy absorbed[3] (kJ)	Peak displacement sensor[4] (mm)	Residual bolt displacement measured (mm)
SMDX-1	2,286	2,132	6.47	47.8	368	262	50.8	194	bar failure
SMDX-2	2,286	2,170	6.52	48.7	340	252	49.5	197	bar failure
SMDX-4	2,286	2,236	6.62	50.1	384	277	56.1	203	bar failure
SMDX-5	2,286	2,234	6.62	50.1	345	255	52.8	207	bar failure
SMDX-6	2,286	2,103	6.42	47.2	358	259	49.0	189	190
SMDX-8	2,286	1978	6.23	44.4	368	264	47.4	179	185
SMDX-9	2,286	1,892	6.09	42.4	325	243	43.9	181	175
SMDX-10	2,286	1,734	5.83	38.9	323	264	42.1	159	165
SMDX-11	2,286	1,556	5.53	34.9	330	254	38.3	151	145
SMDX-12	2,286	1,376	5.20	30.9	307	236	31.8	135	130

1. Input energy is to the point of impact between the loading mass and the bottom nut; it does not include the additional energy applied during the elongation of the test sample; 2. AIL = Absorbed Energy/peak displacement; 3. Absorbed energy is calculated using the measured load and calculated displacement; 4. Sensor displacement is calculated by double integration of the measured acceleration of the claws

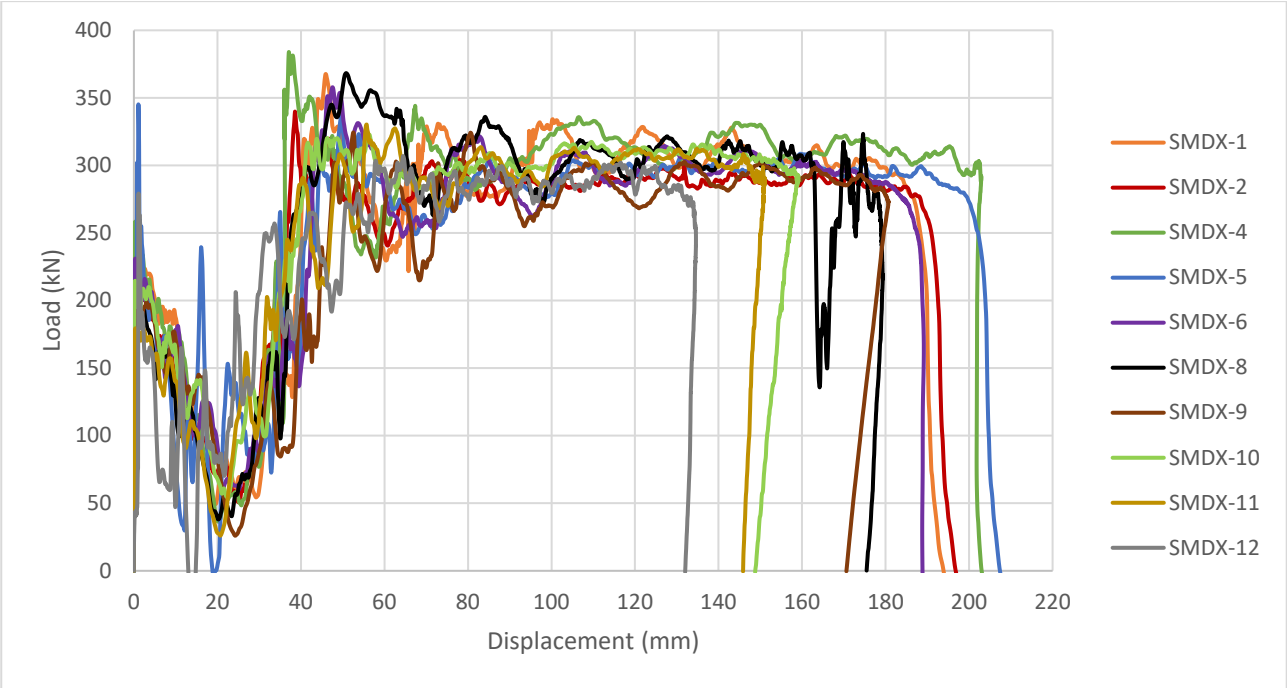


Figure 12 In situ dynamic testing response

Figure 12 shows the consistent performance of the SMDX during dynamic loading, where the bolt shows an initial peak, followed by a drop in load, which is the load overcoming the static friction between the wedges. When the wedges are firmly expanded, the load increases again to the peak and shows a similar response profile as seen when testing the bars only (see Figure 4). This performance shows that when a lower dynamic energy is applied to the SMDX, the only change in the load response is the elongation of the bar.

Part of the in situ testing regime was a series of quasi-static pull tests, which would be performed as part of any routine installation quality testing regime. All samples were tested to a peak load above the yield load between 230–250 kN, as little would be learned from taking the bolts to destruction in this environment. The results from the static testing are shown in Table 5 and the load displacement response is shown in Figure 13.

Table 5 In situ static testing results

Sample	Peak load (kN)	Displacement at peak load (mm)
SMDX-1	240	75
SMDX-2	240	86
SMDX-3	250	81
SMDX-4	240	94
SMDX-5	240	88
SMDX-6	250	78
SMDX-7	240	86
SMDX-8	230	96

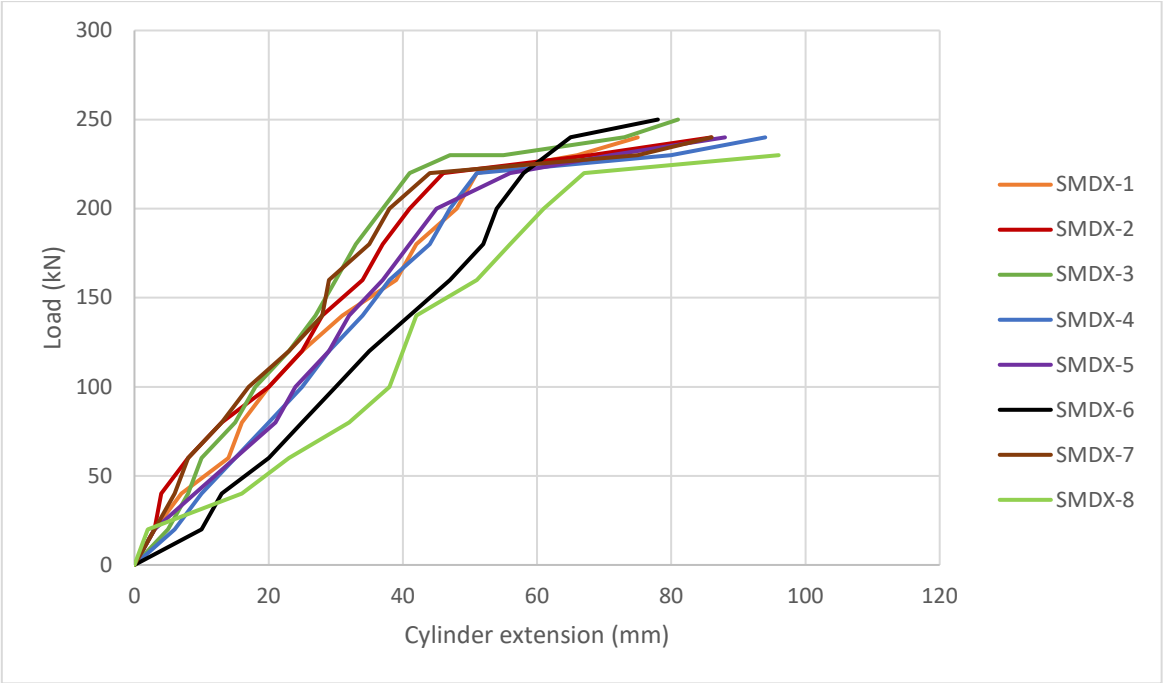


Figure 13 In situ quasi-static test response

5 Discussion

The static testing comparison showing laboratory tensile test sample S-2, the BIT 'push' test sample and in situ test sample SMDX-4 is shown in Figure 14. This plot provides an understanding of the difference between the 3 different methods of static testing; laboratory component, laboratory assembly 'push' testing and in situ assembly pull testing. This comparison shows that the initial stiffness of the bolt is lower in the in situ testing, which can be caused by rock face compression or further wedge engagement, as the tubes did not slide out of the borehole during the static testing. Also, the load recorded for the BIT 'push' test was on average 35 kN higher than the laboratory tensile test, which is attributed to the force required to 'push' the front block over the bolt tube (which is anchored inside the anchor block). When comparing the BIT 'push' test and in situ pull test, the initial performance follows a somewhat similar stiffness, and the yield profile is similar. This is due to the 2 test methods both include the wedge system and rock plate in the test set-up, which can 'soften' the initial load stiffness.

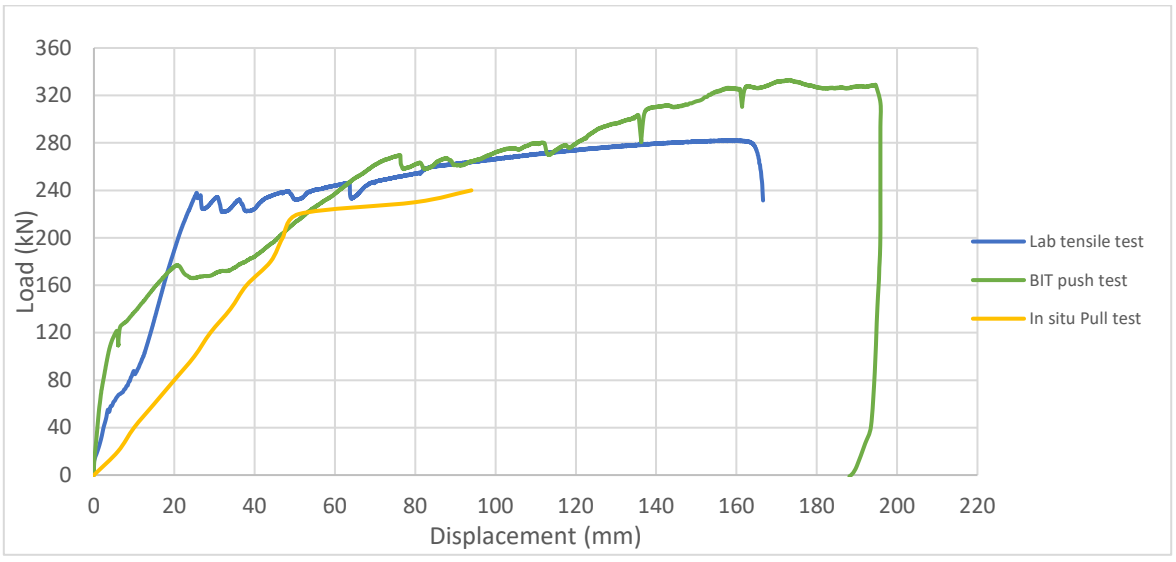


Figure 14 Static testing comparison

Similarly, to provide a comparison of the dynamic testing response between the 3 different testing methods, Figure 15 illustrates the maximum stable results for the laboratory component (D-4), laboratory assembly (LD-2) and in situ dynamic testing (SDMX-6).

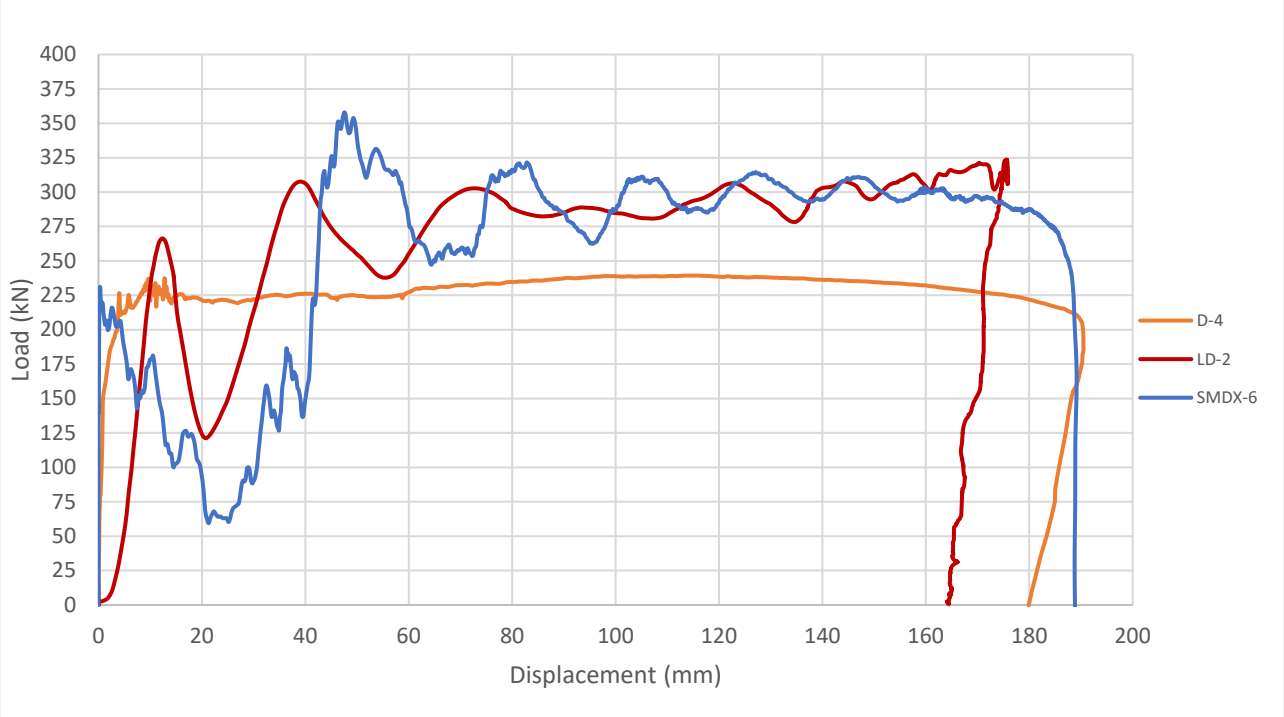


Figure 15 Dynamic testing comparison

This comparison shows a clear difference between the component and assembly testing, where the assembly testing load drops after an initial peak. As mentioned earlier, this is due to sliding and expanding of the wedge mechanism before full wedge expansion and bar stretch. Another interesting observation is the difference in sustained load between the 2 different methods, where the component testing shows a sustained load around 230 kN, whereas the assembly testing shows between 275–325 kN.

The consistent performance of the SMDX through the 3 different test methods demonstrates a robust bolt design, where the maximum stable results for the 3 different test methods were between 45.9, 46.6 and 47.2 kJ.

Based on this range of testing, the Super MDX bolt has a tensile capacity of 270 kN, an in situ dynamic capacity of 47.1 kJ (dissipated input energy without failure), and a wedge system that can expand up to 68 mm.

The in situ testing showed the success of the SMDX bolt when tested with standard installation equipment and using standard installation tools and practices. The results from the 3 different test methods show a close correlation of static and dynamic performance when tested to destruction.

With the successful testing of the SMDX under 3 different conditions, with closely corelating results, the next stage of the product development and release cycle is to perform a larger scale underground site trial. This will involve installing the SMDX bolt over several drill and blast cycles to determine the installation behaviour along with the performance of the bolt during blasting and rock movement conditions. Additionally, more in situ dynamic testing should be conducted across a variety of ground conditions, to obtain a larger sample set of data and to determine whether the performance of the SMDX bolt is dependent on ground conditions.

Acknowledgement

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