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Full-range strain monitoring of rockbolts using the xCell Hydra instrumentation system

Osvaldo Vallati [a,*], Christian Reich [a], Steven Weaver [a]

[a] *Sandvik, Australia*

Abstract

The xCell Hydra system represents a new generation of instrumented ground support technology that integrates fibre Bragg grating (FBG) sensing into rockbolts to provide continuous, high-resolution measurements of axial strain along the reinforcement element for the entire capacity of the bolt.

Traditional instrumentation methods in underground support, such as surface-mounted gauges or point-displacement transducers, are constrained by limited measurement range, spatial resolution and installation complexity. In contrast, the xCell Hydra system embeds an array of ruggedised FBG sensors within a helical groove along the bolt shaft, enabling distributed, multi-point, high-range strain measurement with minimal impact on mechanical performance and improved cable management.

The technology is designed to be compatible with any threaded bar or bolt intended to be fully or partially embedded in resin or grout. Once installed, the instrumented bolt provides detailed strain measurements at each FBG sensor location, allowing operators to monitor load transfer, identify zones of high demand, and assess consumed capacity over time. During loading, each FBG sensor responds to local bolt deformation through wavelength shifts that are converted to engineering strain using a calibrated transfer function. This provides high-fidelity insight into bolt behaviour across the full loading regime, including elastic response, yield onset, load redistribution along the bolt length, and plastic deformation.

This capability is especially valuable in caving operations, where large, rapidly evolving deformations demand reliable insight into support performance as the cave propagates and ground conditions deteriorate. Other applications in caving operations include asset monitoring, rehabilitation and ground support optimisation.

The xCell Hydra technology has been applied to Sandvik's Posimix bolts. Laboratory investigation results demonstrate excellent linearity, low noise and stable performance, highlighting the suitability of FBG-instrumented bolts for demanding underground environments.

The paper first reviews current instrumented bolts described in the literature and their limitations. It then introduces the Hydra technology, explains the basics of FBG measurement principles, and reports the laboratory testing program undertaken to validate the approach.

Keywords: *rockbolt, ground support, monitoring, capacity, xCell Hydra*

1 Introduction

Cave mining operations are carried out in some of the harshest geotechnical settings, where deep excavations are continually exposed to intense, fluctuating stress conditions that drive large deformations, seismic shaking and progressive deterioration of the surrounding rock mass. As the cave propagates and the associated induced stress field migrates, extraction level infrastructure often undergoes substantial closure, uplift of the floor, lateral squeezing and yielding of pillars. These effects are especially severe in weak ground or structurally disturbed zones and can lead to extensive rehabilitation work or even the permanent loss of

* Corresponding author. Email address: osvaldo.vallati@sandvik.com

access. These deformation processes are further aggravated in brittle or heterogeneous rock units and within structurally complex domains capable of producing strainbursts, rockbursts, and other violent failures (Kamp 2022). Under such conditions, the long-term stability of excavations is tightly linked to the performance of ground support systems, which must endure dynamic loading while accommodating static deformation. As loading is progressively transferred from the mobilising rock mass into the reinforcement, support elements steadily expend their capacity, manifesting as bent plates, torn mesh, elongated or ruptured bolts and other forms of distress. Because this degradation occurs incrementally as deformation accumulates, understanding how much capacity has been consumed and how the reinforcement system is deteriorating over time is essential for maintaining safety and functionality in deep cave mines.

Literature reviews of instrumented rockbolts have been carried out using several authors' methods (Song et al. 2017; Vallati et al. 2020; Lama & Momayez 2023). Traditional instrumented bolts that rely on electrical resistance or vibrating wire strain gauges bonded within machined grooves have long been used to monitor axial loading along fully grouted bolts, but their performance is constrained by several intrinsic limitations. Early configurations typically employed short-base gauges less than 20 mm in length, installed in longitudinal grooves, which meant that less than 10% of the bolt is monitored; as a result, peak loads were frequently underestimated or missed altogether because strain concentrations occurring between gauge locations remained undetected. Although later designs incorporating long-base gauges provided greater coverage (Hoehn et al. 2020), they still tended to smooth or average out sharp strain gradients, obscuring the true load transfer mechanisms that develop around fractures and bedding plane separations. Another disadvantage is that strain values obtained from non-standardised gauge lengths cannot be directly compared with published steel-bolt specifications, leading to errors when estimating consumed capacity. Collectively, these limitations have restricted the widespread application of traditional strain-gauge instrumented bolts in highly deforming caving operations, where continuous and accurate full-length load characterisation is essential for evaluating support performance.

Fibre-optic instrumentation emerged as a major advancement over traditional strain-gauge systems, offering the potential for optimised strain measurement along the full length of a fully or partially grouted bolt. Early implementations were based on fibre Bragg gratings (FBGs) by Dong et al. (2022) and Rayleigh-based distributed optical sensing (DOS) by Hoehn et al. (2020), with fibres installed in machined longitudinal slots to capture axial shear and bending responses at far higher spatial resolution than electrical gauges. FBG sensors provided point-based measurements at discrete locations along the fibre, whereas DOS technologies enabled quasi-continuous strain profiles with resolutions as fine as 0.5 mm, allowing researchers to detect localised deformation features that conventional systems frequently missed. Although fibre-optic systems provide significantly higher spatial resolution than traditional strain-gauge instrumentation, all current optical technologies remain constrained by their intrinsic strain-capacity limits. In practice, the maximum measurable deformation of FBG and Rayleigh-based DOS is far below the levels that fully grouted bolts may experience in highly deforming cave environments, where steel reinforcement can undergo tens of per cent axial elongation before rupture. As a result, even the most advanced fibre-optic bolts cannot yet capture the full deformation envelope that real ground support elements may sustain. Furthermore, fibre-optic bolts were expensive to manufacture due to the need for precision slotting, fibre placement, and delicate connectors, which were often damaged during installation.

Despite these constraints, FBG-based systems still offer compelling technical advantages. However, a significant gap remains in the industry for instrumented bolts that are simple to install, compatible with standard bolting practices, and capable of providing reliable full-range performance data. This unmet need for a practical, easily deployable monitoring solution motivated the authors to pursue the development of a new fibre-optic monitoring system based on FBG technology, the xCell Hydra.

2 The technology

2.1 Loading distribution of encapsulated rockbolts

In fully encapsulated rockbolts, axial load is transferred through shear interaction mobilised at both the bolt–grout and grout–rock interfaces, allowing the bolt to engage progressively with the surrounding rock mass as deformation occurs. Laboratory, analytical and numerical studies, such as those by Chen (2012), Ma (2014) and Li et al. (2016) consistently demonstrate that axial force and interface shear stress reach their maximum values either at the location of a discontinuity or near the collar and then decay along the embedment length following an exponential attenuation. As deformation increases, a debonding zone typically initiates at the joint opening or collar and propagates down the bolt. Regions farther from the initiation point remain in elastic or partially bonded states depending on grout quality, confinement, and installation conditions. Moreover, the efficiency of this load transfer mechanism is strongly influenced by the quality of the grout or resin, as poor mixing, gloving, voids, low-strength resin, or inadequate encapsulation can substantially reduce anchorage strength, interrupt shear stress continuity and alter the axial strain distribution along the bolt, ultimately weakening the load transfer capacity of the reinforcement system (Figure 1).

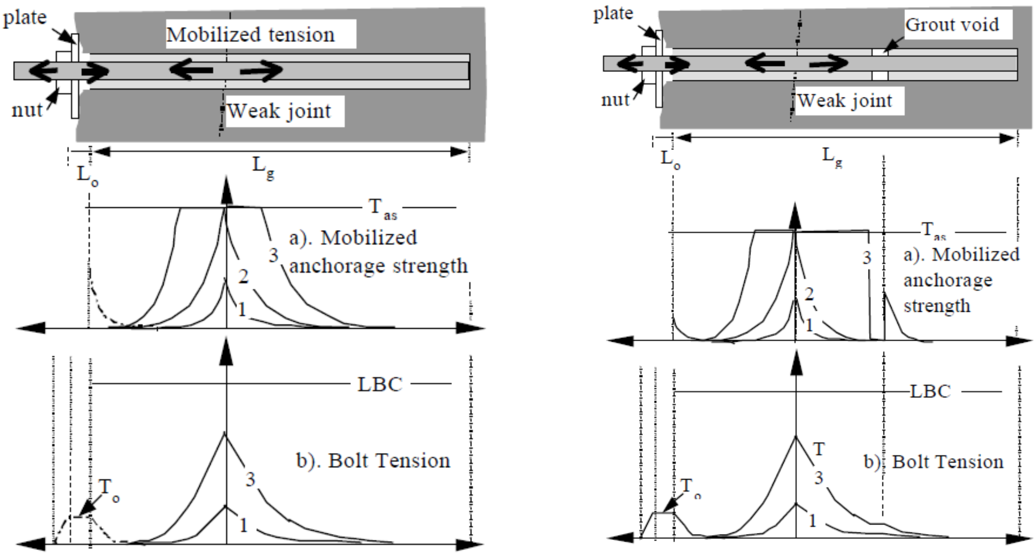


Figure 1 Tension mobilisation in encapsulated rockbolt (after Zou et al. 2004)

Given these highly localised, rapidly varying strain gradients and the inherently non-uniform tension distribution that develops along fully encapsulated bolts, FBG technology is exceptionally well suited for detecting the resulting strain profile, offering the spatial resolution and continuous measurement capability needed to resolve the complex load transfer behaviour in situ.

2.2 Fibre Bragg gratings

Fibre Bragg grating technology is a sensing method based on periodic refractive-index variations inscribed along the core of an optical fibre, which act as wavelength-selective reflectors. When the fibre is subjected to strain changes, see Figure 2, the spacing of these gratings shifts, producing a measurable change in the reflected wavelength that can be precisely correlated to axial deformation.

Because the sensing mechanism is intrinsic to the fibre itself, FBG sensors offer several advantages for instrumented rockbolts: they are inherently immune to electromagnetic interference, capable of delivering highly accurate strain measurements, and can be multiplexed to host multiple sensing points along a single fibre with minimal signal attenuation. In addition, the fibre's small diameter means that only minimal modification of the rockbolt is required to accommodate the sensor.

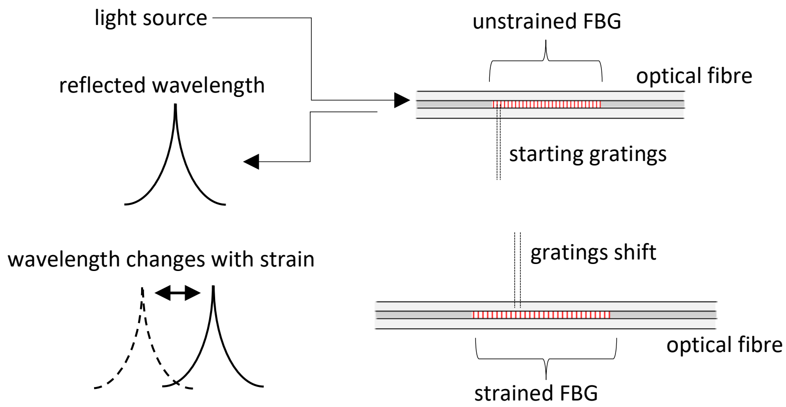


Figure 2 Fibre Bragg grating sensing technology

2.3 Application of FBG sensing to Sandvik's rockbolt for full-range strain monitoring

The authors applied the FBG sensing technology to Sandvik's solid bolts, beginning with the Posimix range. The Posimix bolt is a high-performance resin-anchored reinforcement system that delivers excellent load transfer and exceptional deformation capacity owing to its helical mixing design and reliable resin encapsulation (Sandvik 2024).

Standard FBGs can reliably capture strains only within approximately 1–3% (occasionally up to ~4%) before the silica fibre reaches its mechanical limit, whereas steel rockbolts can normally sustain 10–20% elongation This mismatch has historically constrained the application of optical sensing on yielding bolts. However, the approach demonstrated by Schroeck et al. (2000) provides a practical solution: by installing the fibre in a mathematically calculated helical groove, with the pitch determined from bolt diameter and the Poisson's ratio, the fibre experiences a significantly reduced effective strain relative to the steel substrate.

Applied to Sandvik's Posimix bolts, this concept enables full-range strain monitoring while preserving the mechanical performance of the reinforcement. The helical groove required for housing the fibre is extremely shallow, approximately 1 mm deep, which is sufficient to protect the fibre yet small enough that it does not meaningfully reduce the bolt's load-carrying capacity or structural integrity.

For the laboratory investigation in Section 3.3, an optical fibre with 9 FBGs (i.e. 9 stain measurements points) was used to instrument the Posimix bolt (Figure 3a).

In line with established practice for instrumented reinforcement, the fibre is routed through a recess machined into the bolt head (Figure 3b), allowing the optical connector to sit protected within the cavity. This ensures the interrogator interface remains mechanically shielded while maintaining a continuous fibre path along the helical groove of the bar.

To establish a controlled gauge length that aligns with international tensile testing standards, the instrumented bolt incorporates a debonding sleeve, a short tubular section that isolates the FBG from the steel, so the fibre can elongate independently over a defined interval. The sleeve creates a free section of optic fibre that is no longer bonded to the helical groove but displaces proportional to the steel. This enables the sensor to record an averaged strain over a prescribed gauge length rather than a point measurement (few millimetres long). In practice, this gauge length is selected according to ISO 15630 (International Organization for Standardization 2019) and ASTM E8/E8M (ASTM International 2021) and can be calculated as a function of bar diameter. A 100 mm-long gauge was used in this laboratory testing for the 20 mm-diameter Posimix bolt. This gauge length enables direct comparison between the measured strain response and the published mechanical properties of the bolt (Sandvik 2024).

The final assembly also incorporated several practical features: a protective cap to shield the connector from dirt and debris; a longer nut to ensure adequate mechanical engagement given the thread-capacity reduction caused by the machined helical groove; and a low-profile protective rubber tubing to safeguard the bolt during handling and installation (Figure 3c).

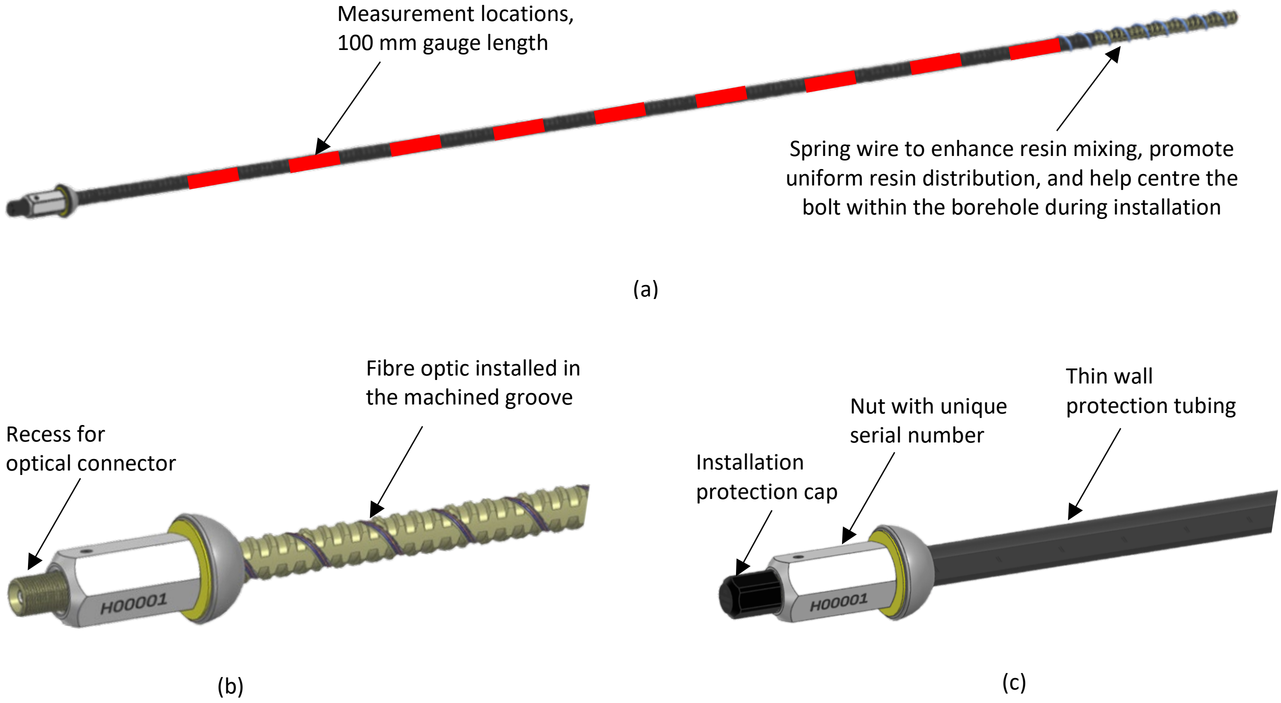


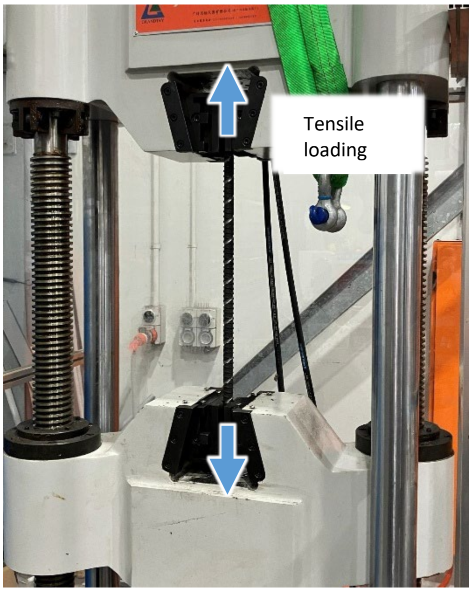
Figure 3 Fibre-optic instrumented Posimix bolt, 2,400 mm long, with 20 mm-diameter threaded bar. (a) Instrumented Posimix showing conceptual location of the FBG sensors; (b) Detail of the instrumented Posimix; (c) Instrumented Posimix showing the protection tubing and the installation protection cap

3 Laboratory testing

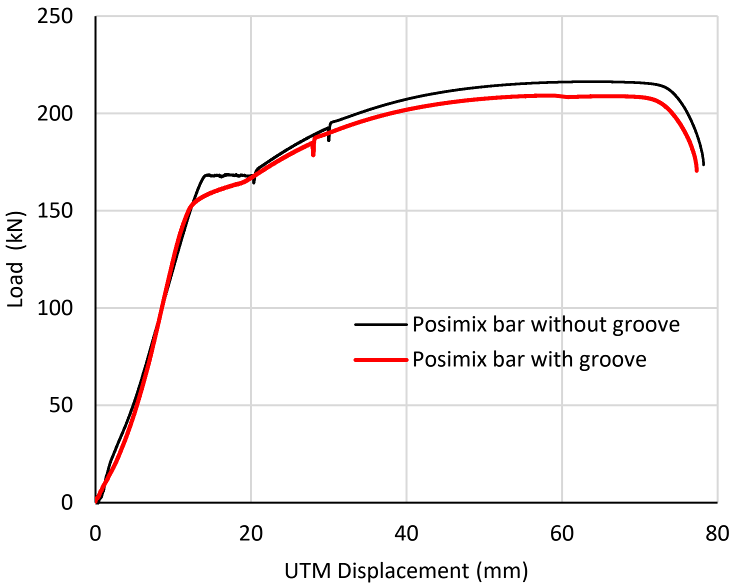
To validate the performance of the instrumented bolt system, a laboratory testing program comprising three test series was undertaken: a mechanical strength test to assess whether the helical groove affected the bolt's strength, calibration testing in a universal testing machine (UTM) to verify the FBG strain response, and a full bolt installation and loading test to evaluate system behaviour under realistic installation and loading conditions.

3.1 Test series 1: tensile testing on the impact of the machined groove

The first test series aimed to determine whether machining a helical groove into the Posimix steel bar altered its mechanical performance. Several specimens with varying groove minor diameters, groove radii, and groove pitch were tensile tested in Sandvik's Research and Development Laboratory using a UTM. The grooved specimens were directly compared against an unmachined control bar to quantify any reduction in strength or ductility; each sample was 500 mm long with a free length of 350 mm. Figure 4 presents the test set-up and the results of the final design iteration. The comparison demonstrates that the shallow groove does not measurably degrade the tensile capacity or elongation of the bar, confirming that the optical fibre groove geometry is mechanically compatible with the required performance. The shallow helical groove removes only a small amount of material and distributes it along the bar length, preserving a continuous load path and resulting in only a minor reduction in strength.



(a)



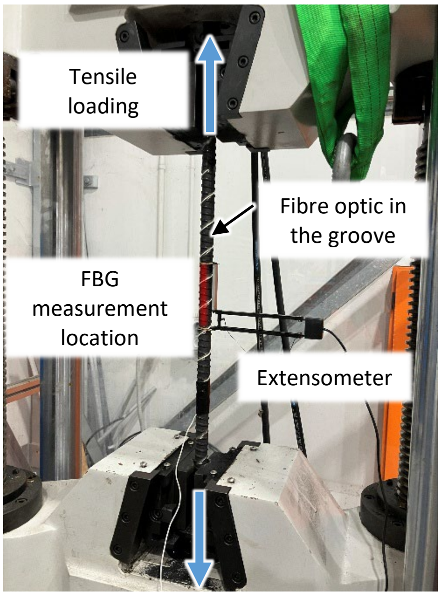
(b)

Figure 4 (a) Universal testing machine (UTM) tensile test set-up for the sample with groove; (b) Test results: load–displacement plot for Posimix bars with and without groove

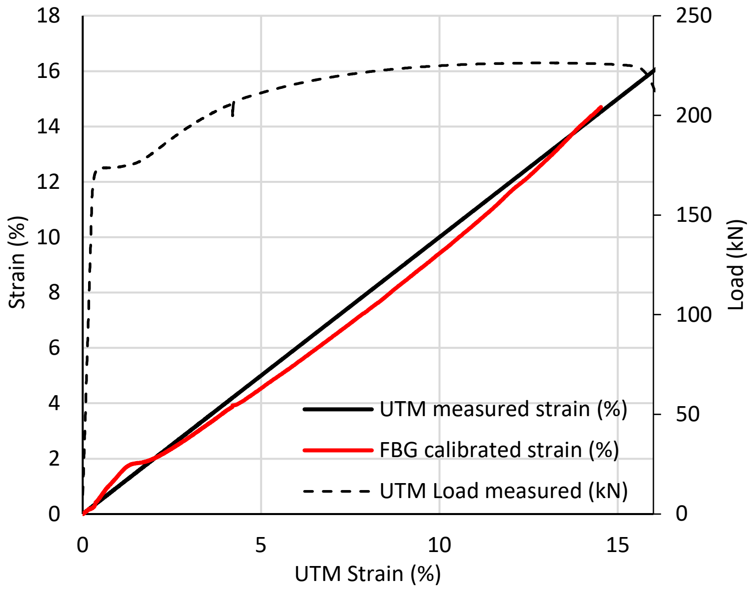
3.2 Test series 2: tensile testing for FBG validation

The second test series focused on validating the strain measurements obtained from the FBG sensors during tensile loading. A 650 mm-long portion of a Posimix bar instrumented with FBG sensors was tensile tested in the UTM under displacement control. The free length of the sample between the testing machine jaws was 540 mm. Strain was recorded simultaneously using the UTM instrumentation and the embedded FBG sensor. The UTM extensometer (gauge length = 100 mm) was used as the reference measurement up to 3 % strain, after which strain was derived from the machine displacement and grip separation.

By comparing the raw FBG strain output against the reference UTM strain (Figure 5), calibration factors were established to generate a corrected FBG strain response. After calibration, the corrected FBG strain closely tracked the UTM-derived strain throughout the loading sequence, including up to the peak load before necking occurs. The FBG system demonstrated stable and repeatable strain monitoring, with good similarity to the UTM strain curve across the entire deformation range. These calibration factors were subsequently applied to the complete dataset and to all further instrumented tests.



(a) UTM test set-up



(b) Test results: solid red line represents the strain measured by the xCell Hydra system, obtained from the raw FBG strain readings after applying the appropriate calibration factors.
Solid black line shows the reference strain measured by the UTM, which is used as the benchmark for comparison.
Dashed black line displays the UTM load–strain response of the specimen.

Figure 5 (a) Fibre Bragg grating validation testing in the universal testing machine; (b) Test results

3.3 Test series 3: bolt installation and loading test

Test series 3 focused on evaluating the strain response of two instrumented Posimix bolts during realistic installation and subsequent axial deformation using Sandvik's Bolt Installation Test (BIT) stand. The BIT was originally developed by Darlington et al. (2024) for controlled percussive installation trials of mechanical bolts, but adapted for this program to enable both resin bolt installation and post-installation push-testing of the bolt.

In the first phase, for bolt installation, the BIT was configured as shown in Figure 6. Two composite steel–concrete blocks (250 × 250 mm cross-section, 1,200 mm length) served as the host ground medium. The front block incorporated a pilot through-hole, while the rear block contained a 1,100 mm-long blind pilot hole. Each block also featured two transversal square through-holes. These through-holes formed part of the clamping system used to hold the blocks tightly together during installation, preventing any resin egress or block separation, and were used again when configuring the assembly for push-testing.

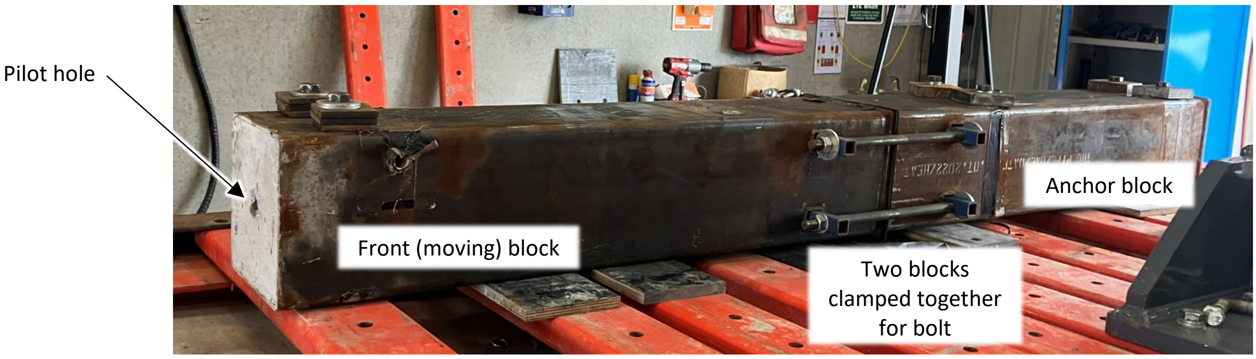


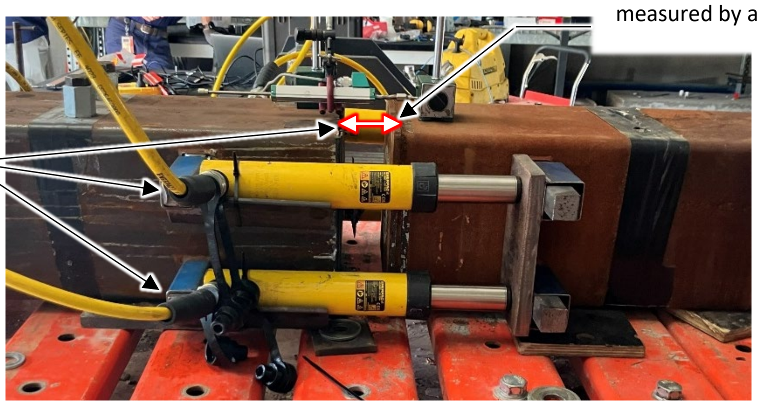
Figure 6 Sandvik's bolt installation test stand fitted for resin bolt installation

As per industry practice for resin-anchored Posimix bolts, the hole was first drilled using a 35 mm nominal drill bit. Pre-packaged resin capsules (Fasloc® medium-slow resin) were then inserted into the borehole in preparation for anchoring. The Posimix bolt was subsequently pushed and rotated into the hole, allowing the spring wire and helical ribs to rupture and mix the resin, ensuring thorough distribution throughout the annulus. Once fully inserted, the bolt was held stationary until the fast-setting resin component hardened at the toe. After resin curing, the nut was torqued to complete the installation.

With the bolt fully installed, the assembly was left to cure for 24 hours before the rig was reconfigured for push-testing.

The clamp holding the two blocks together was removed, and transversal through-pins were inserted into the square through-holes in each block. Four hydraulic cylinders were then installed within the designated cradles and connected to a battery-driven pump via a 4-in-1 manifold, ensuring that the hydraulic load was evenly distributed across all cylinders. During push-testing, extension of the cylinders increased the separation between the two concrete blocks, effectively pushing the assembly apart, as shown in Figure 7. This imposed axial displacement onto the installed bolt, simulating ground-induced deformation while preserving realistic confinement and boundary conditions provided by the two concrete blocks.

(a)



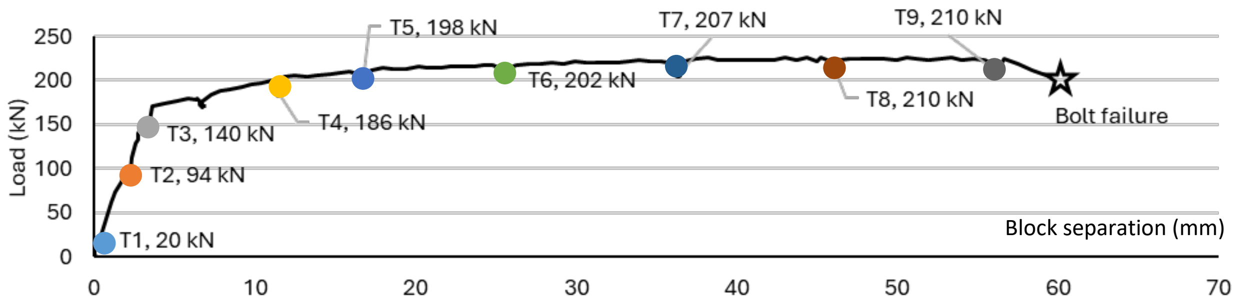
(b)

Figure 7 (a) Bolt installation test set-up for bolt push-testing; (b) Detail of hydraulic cylinders and block separation

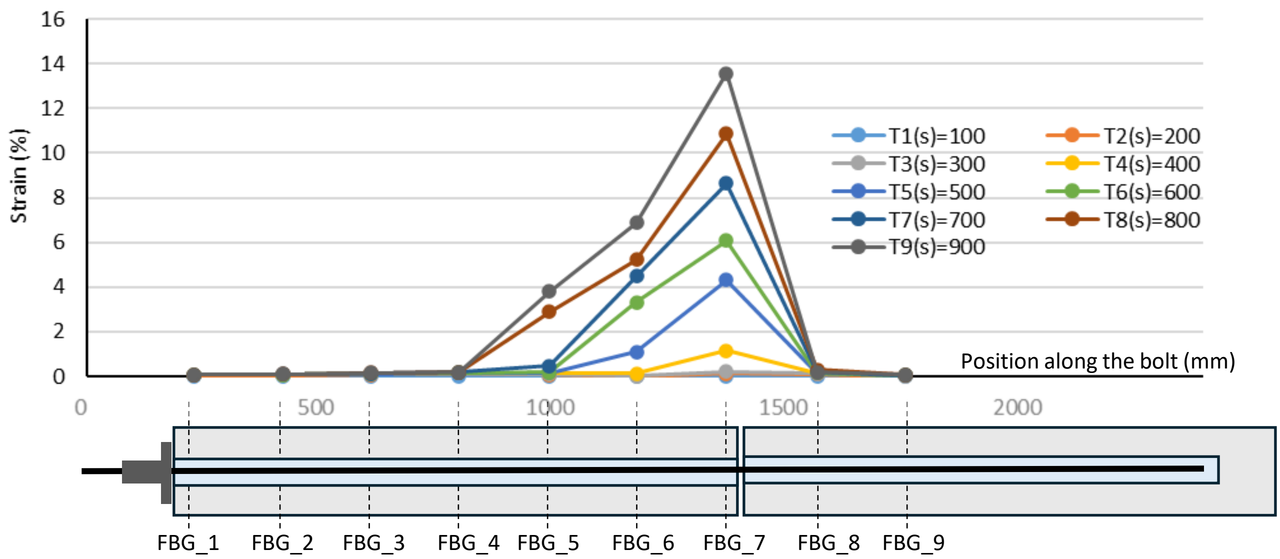
Strain profiles along the bolt were recorded continuously by the optical sensors throughout the loading test. Block separation was measured using a linear variable differential transformer (LVDT), while the applied load was monitored through a pressure transducer connected to the hydraulic system.

Two tests are presented in this paper, and the results are shown in the paragraphs below. The data is shown as strain profiles along the bolt at different time steps during each test. For completeness, the corresponding load–displacement curve, derived from the LVDT measurements and the pressure transducer readings, is also included.

Figure 8 shows the response of Sample 1, presenting both the global load history and the strain distribution along the bolt at key time steps. The load–displacement curve appears typical for a fully encapsulated Posimix bolt, with yielding occurring around 185 kN and the load continuing to increase steadily until failure (Figure 8) at approximately 210 kN. Throughout the test, the FBG sensors captured the evolution of strain along the bolt, revealing a pronounced localisation of deformation in the central region between FBG_5 and FBG_7, corresponding to the separation plane between the two concrete blocks. As loading progressed from time T1 to T4 (i.e. from 100 seconds to 400 seconds), the strain remained relatively evenly distributed along the bar; however, once yielding commenced, strain concentration became increasingly pronounced around the block separation, ultimately forming the localised deformation zone that preceded bolt failure. The highest strain was recorded by FBG_7, reaching approximately 14 % near peak load, immediately before failure. This maximum strain level is consistent with the tensile response observed in the UTM tests shown in Figure 4. Sensors positioned closer to the collar (FBG_1–FBG_4) and those near the toe (FBG_8–FBG_9) showed minimal strain, indicating limited load transfer in those zones. The FBG measurements show localised strain development along the bolt that is not captured by collar displacement or plate load observations only, highlighting the improved understanding of bolt behaviour and the potential for misinterpretation when relying on collar-based measurements alone.



(a) Load–displacement plot



(b) Strain profile along the bolt

Figure 8 Test results for Sample 1

Figure 9 Overview of Sample 1 after failure

Figure 10 presents the response of Sample 2, showing both the load–displacement behaviour and the strain distribution along the bolt at selected time steps. The load–displacement curve follows the same pattern observed in the previous test; however, in this case, the bolt experienced a substantially larger total displacement before failure. While Sample 1 failed at approximately 60 mm of block separation, Sample 2 reached about 85 mm, indicating a greater deformation capacity. This higher deformation capacity can be explained by examining the FBG strain profile, which shows that a longer portion of the bolt was engaged in deformation compared with Sample 1. The zone experiencing significant strain, above 2% (well into the yielding range of the steel), extended over nearly 1 m of bolt length in Sample 2, whereas in Sample 1 the corresponding deformation zone was limited to roughly 650 mm. This longer active deformation region allowed the bar to accommodate greater overall deformation before failure. The peak strain was recorded at FBG_6, exceeding 16% immediately before failure. Sensors FBG_1–FBG_3 remained at low strain throughout the test, indicating good load transfer and effective anchorage at the collar end.

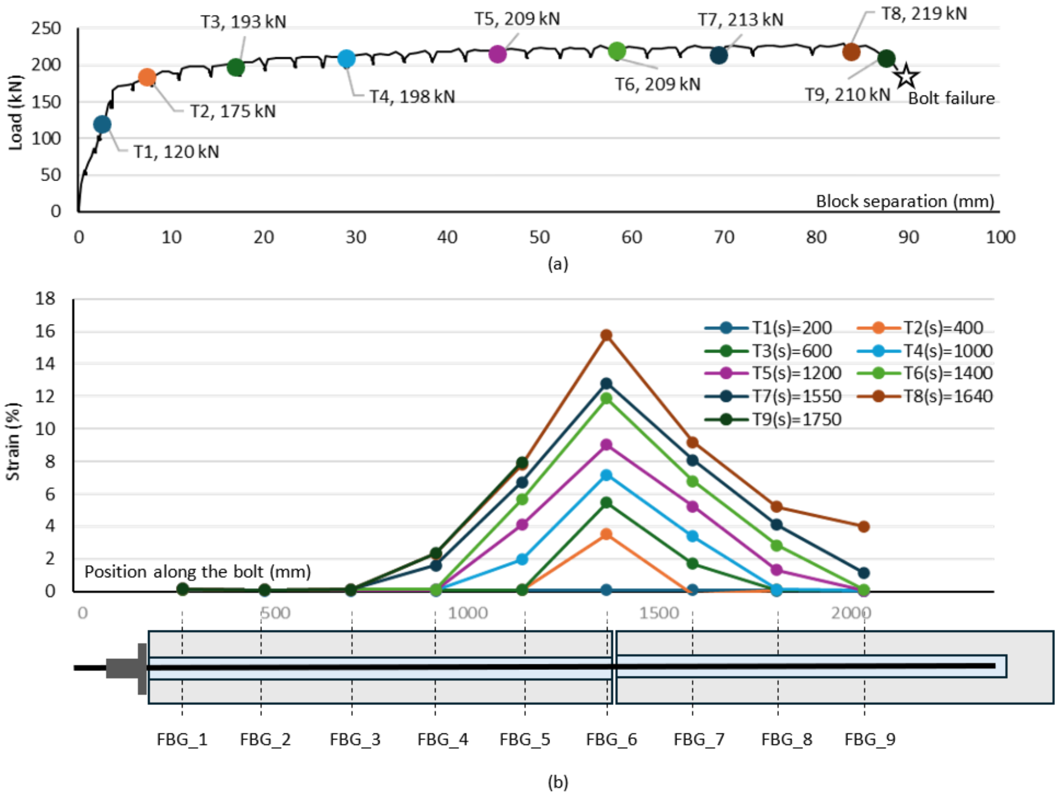


Figure 10 Test results for Sample 2. (a) Load–displacement plot; (b) (a)Strain profile along the bolt

Overall, the results from test series 3 demonstrate that the BIT configuration, resin-anchored installation procedure and distributed FBG instrumentation collectively provided stable, high-quality measurements, confirming that the method is effective for capturing bolt deformation behaviour under realistic loading conditions.

4 Underground deployment model and customer value

The system is designed to enable practical, scalable deployment of instrumented rockbolts in underground environments, using an approach that closely follows the operational model already established for Sandvik's xCell Cyclops™ system (Vallati et al. 2023). Figure 11 presents a conceptual overview of the system. Once installed, each instrumented bolt is connected to an xCell Hydra. The xCell Hydra is the multi-channel datalogger that provides a fully wireless, battery-powered monitoring solution designed specifically for harsh mining conditions. The device incorporates Wi-Fi and Bluetooth connectivity, allowing simple installation, full compatibility with the xCell Professor, and automated data transfer to Sandvik xCell digital ecosystem.

Once the instrumented bolt is installed, the optical lead is connected directly to the xCell Hydra. From this point, the xCell Hydra operates autonomously, recording strain changes captured by the embedded FBG array. Data packets containing bolt deformation, strain rates, and system status are transmitted wirelessly at scheduled intervals, enabling operators and geotechnical engineers to access real-time bolt-level information, alarm states, and location-grouped dashboards through the xCell platform.

Because xCell Hydra is fully battery powered and requires no underground cabling or infrastructure, deployment can be carried out alongside routine ground support activities without disrupting development schedules. The xCell Hydra hub can monitor up to nine instrumented bolts simultaneously, with user-defined recording rates and a battery life of up to 3 years in typical deployments.

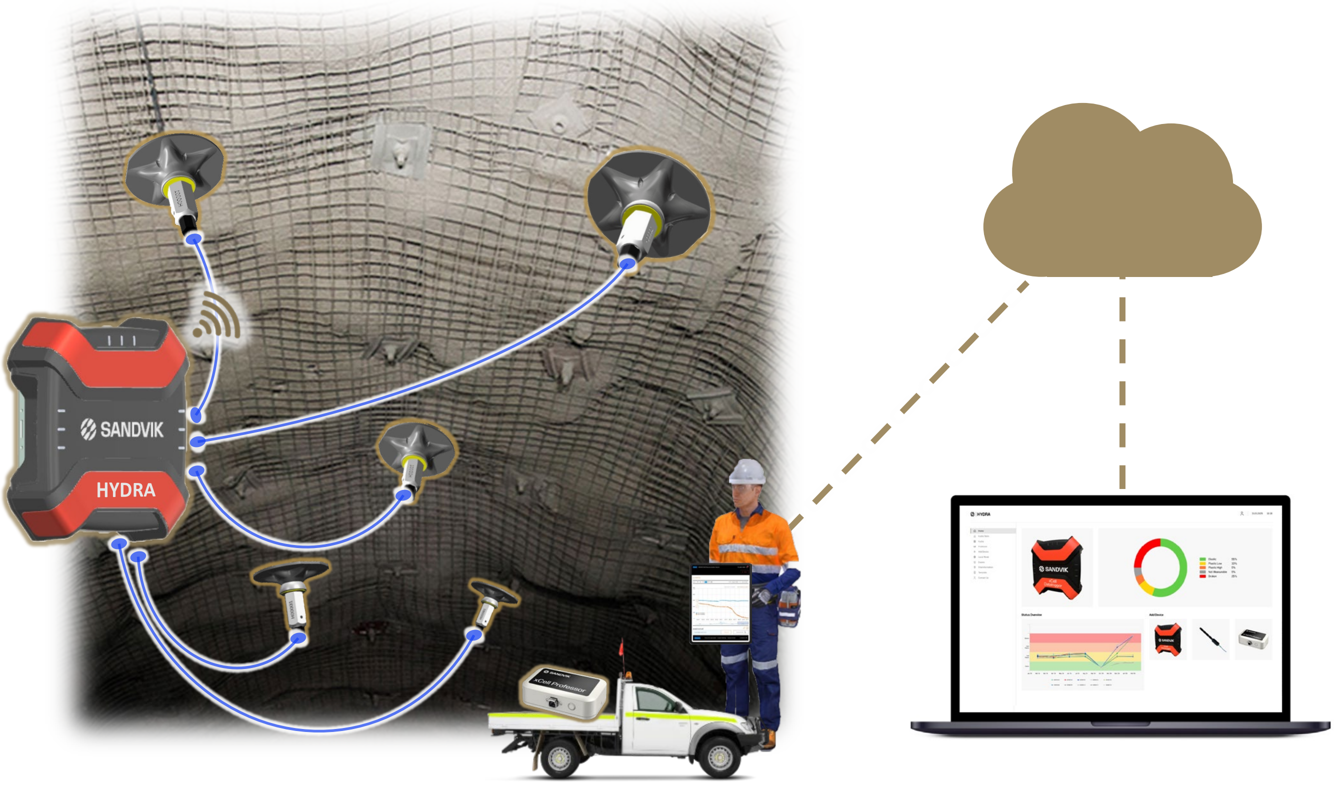


Figure 11 Overview of xCell Hydra deployment underground

From a user perspective, the xCell Hydra system unlocks a range of high-value use cases that directly enhance underground operational safety and decision-making. One of the key benefits is early hazard detection: by continuously tracking deformation along each instrumented bolt, xCell Hydra allows geotechnical engineers to identify changes in load transfer, stress accumulation and the onset of yielding well before any visible signs of instability appear. This early warning capability supports proactive interventions, such as targeted secondary support, barricading or local rehabilitation, reducing the likelihood of unplanned ground control incidents. In practical terms, the xCell Hydra system enables alarm- and threshold-based triggers for intervention based on real measured strain.

Beyond early detection, the system provides a robust foundation for data-driven ground support optimisation. The strain data collected by xCell Hydra offers direct insight into bolt demand, load transfer mechanisms and yield progression. Over time, these empirical datasets allow engineers to refine support designs, resin encapsulation practices, and bolt selection strategies, enabling a shift away from conservative, assumptions-based design philosophies towards performance-based verification grounded in real measurements.

xCell Hydra also enhances rehabilitation planning and resource efficiency. Because the system reveals which areas are consuming bolt capacity most rapidly, mines can prioritise interventions where they will have the greatest impact, rather than relying solely on periodic visual inspections or time-based schedules.

The technology further strengthens quality assurance and installation verification. By monitoring strain behaviour immediately after installation, the xCell Hydra can highlight underperforming bolts resulting from inadequate resin mixing, incomplete encapsulation or tensioning errors. This rapid feedback loop allows operators to address installation issues early, improving overall support integrity and repeatability.

In addition, the distributed strain measurements provided by xCell Hydra offer a deeper understanding of ground behaviour at depth. The ability to observe both localised and distributed deformation along the bolt helps engineers interpret failure mechanisms, assess the contribution of different strata or structures to ground movement, and refine geotechnical models that inform mine design and sequencing decisions.

A particularly valuable use case emerges when xCell Hydra technology is applied in seismically active ground on dynamic rockbolts such as debonded Posimix bolts. In these conditions, strainbursting and sudden rock mass bulking are the dominant damage mechanisms, and understanding the depth and extent of dynamic damage is critical for deformation-based support design (Kaiser 2014). xCell Hydra's distributed strain measurements can capture the depth of strainburst-induced deformation and provide clear indicators of the strainburst depth and the extent of rock mass bulking.

Finally, xCell Hydra contributes to regulatory compliance and safety assurance by generating continuous, auditable records of support performance and capacity consumption. These data streams strengthen documentation for statutory reporting and provide evidence-based justification for ground support design decisions, further enhancing operational transparency and safety governance.

Together, these capabilities make xCell Hydra a truly scalable solution that, when combined with complementary systems such as xCell Cyclops and xCell Banshee (Vallati et al. 2026), delivers even greater operational insight and reinforces our broader goal of helping the industry achieve safer, more effective and data-driven ground support practices.

5 Conclusion

This study demonstrates that the xCell Hydra system enables reliable, full-range strain monitoring of encapsulated rockbolts by integrating ruggedised FBG sensors within a shallow helical groove along the bolt shaft. Laboratory testing across three complementary programs confirmed that the groove geometry does not compromise bolt strength, that the FBG strain response can be accurately calibrated against UTM reference measurements, and that the instrumented bolts capture realistic deformation behaviour during installation and loading using Sandvik's BIT stand.

By combining a mechanically robust sensing architecture with a wireless, battery-powered datalogger designed for harsh underground environments, xCell Hydra provides a practical pathway for widespread deployment of instrumented bolts in production mining settings. The system delivers high-fidelity strain data that supports early hazard detection, QA/QC verification, targeted rehabilitation and data-driven optimisation of ground support design. When integrated with complementary systems such as xCell Cyclops for convergence monitoring and xCell Banshee for mechanical bolt capacity assessment, the xCell Hydra contributes to a unified, scalable instrumentation ecosystem that enhances situational awareness, supports safer decision-making and helps the mining industry move towards more effective, data-driven ground support practices.

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