Ground Support 2023 – J Wesseloo (ed.)

doi:10.36487/ACG_repo/2325_18

Design, development and testing of the Falcon Bolt

R Galluzzi *Jennmar, Australia*

M Holden *Jennmar, Australia*

A Dodds *Jennmar, Australia*

J Matthews *Jennmar, Australia*

A Bennett *Jennmar, Australia*

Abstract

This paper introduces the Falcon Bolt – a self-drilling hollow bolt with a unique mechanical anchoring system developed for use in the underground hard rock mining environment. The Falcon Bolt aims to deliver several key innovations including reduced installation time, pre-tension during installation and high dynamic capacity. This paper will present the results of comprehensive testing and demonstrate how a data-driven iterative process was implemented to refine the Falcon Bolt's performance characteristics. Testing methods include static pull testing, independent dynamic testing at Canmet and in situ installation verification.

Keywords*: self-drilling bolt, rockbolt installation efficiency, rockbolt design, dynamic ground support*

1 Introduction

The mining industry is continuously striving for dependable ground support systems that increase development rate and reduce implementation costs, but, frequently, the achievement of one objective has been at the expense of another. An analysis of global mining activity between 2004 and 2018 by Canart et al. (2018) demonstrates an increase in total production volume of 35%, while expenditure increased by 275%. This illustrates the imperative for mining operations to enhance their overall productivity by decreasing expenditure per production volume. As accessible ore deposits become depleted, productivity issues are further exacerbated by the need for mining operations to drive through more challenging terrains (Zheng & Bloch 2012). Humphreys (2019) shows that, historically, technological innovation has been the greatest contributor to increases in mining productivity. The pressure to generate technological innovation, therefore, is mounting. A case study conducted at Malmberget mine in Sweden by Bray et al. (2019) suggests that recent advancements in drilling, and truck and loader technologies have significantly increased development rates. Rock reinforcement has now become a potential bottleneck in the development process. The mining industry requires a bolt that enables rapid installation while ensuring consistent installation quality. With a history of innovative self-drilling bolts such as the MPA Bolt, Jennmar has developed the Falcon Bolt to meet this demand. Underground trials have demonstrated the Falcon Bolt's viability as an innovation that can enhance safety and efficiency of ground support operations by providing faster installations, immediate pre-tension and reduced manual handling. Anticipating the future, the Falcon Bolt could readily serve as a foundation for the development of a fully automated installation system. Figure 1 demonstrates the anatomy of the bolt.

Figure 1 Anatomy of the Falcon Bolt

2 Concept formation

A comparison of rockbolt applicability for various conditions (Figure 2) reveals the versatility of the self-drilling bolt, while its installation procedure requires significantly fewer steps, thus reducing manual handling and the time required to complete a bolting process. These advantages identified the self-drilling installation methodology as an important area to invest engineering effort, and potentially as an option that could offer a gain in bolting efficiency. Historically, there have been several barriers impeding the widespread adoption of self-drilling bolts. These include their higher cost, installation issues including decoupling drifter from the bolt, and compatibility with commonly available equipment. Previous attempts at self-drilling methods did not include a system to secure the bolt within the borehole, and instead required purpose-developed resins that are injected immediately after the bolt has been installed (Bray et al. 2019). This method required complex injection mechanisms, the resin can seize the installation equipment to the bolt, and the drilling boom remains inactive while the resin sets, thus slowing down development. Furthermore, existing self-drilling options are not capable of achieving pre-tension. The Falcon Bolt's initial design brief required that the new system must overcome these specific issues. The Falcon Bolt is driven via a hexagonal coupling instead of directly from the threaded bar, eliminating issues decoupling from the drifter, and components were specifically designed with existing drilling equipment in mind. The Falcon Bolt's mechanical anchor is pre-tensioned during installation, securing the bolt within the borehole before grouting and freeing up the drill to begin the next installation.

			SN-Bolt	Self-drilling Bolt	Grouted Bolt	Split-Set	Swellex	Expansion-Shell	Cablebolt
Rock Conditions	Quality of Rock Mass (Strength)	Very Poor Quality Rock Mass		x					
		Poor Quality Rock Mass		x	x				
		Fair Quality Rock Mass		x	x	(x)	(x)		(x)
		Good Quality Rock Mass	x	x	x	x	x	x	x
		Very Good Quality Rock Mass	x	(x)	(x)	x	x	x	x
	Borehole Conditions (Quality of Hole)	Unstable Borehole		x		(x)			
		Brittle Borehole (Fractured)	(x)	x	(x)	(x)	(x)		(x)
		Stable Borehole	x	x	x	x	x	x	x

Figure 2 Comparison of rock suitability for different rock conditions (Türkmen 2009) with x indicating suitability and (x) indicating limited suitability

The Falcon Bolt utilises a top-down resin or grout injection principle completed after pre-tension is achieved. This strategy aims to overcome issues with existing resin bolts, such as difficulties locking in mesh, difficulty inserting resin tubes (especially in collapsed holes), poor resin mixing (underspinning/overspinning/gloving) (Villaescusa et al. 2008) and poor encapsulation as resin is lost to surrounding country. The Falcon Bolt's components are designed to reduce flow obstructions and optimise encapsulation quality using typical pumping equipment. Jennmar has developed the Falcon Bolt in conjunction with a mechanical injection system. When utilised in conjunction with a mechanical injection system, a further increase in bolting efficiency can be gained, resin encapsulation becomes more consistent and the reliance on a grouting crew is removed. The Falcon Bolt is available in various lengths to suit diverse requirements and an extension drilling system has been devised to facilitate installations greater than 3 m in length, offering a potential alternative to cable bolts. To cater for seismic or squeezing conditions, the Falcon Bolt can be supplied in a unique configuration optimised for dynamic performance. The Falcon Bolt and its installation system are protected by patents.

3 Testing and development

3.1 Material selection

The Falcon Bolt can be produced using a range of materials and each will endow the Falcon Bolt with distinct mechanical characteristics. Many material types are initially considered, but two material types, A and B, emerge as prospective contenders. Each material's tensile strength and elongation characteristics are experimentally determined and compared to evaluate their suitability. In static applications, the Falcon Bolt must react to the gravitational load of a rock mass, thus a higher tensile strength is a key design parameter. However, the Falcon Bolt must also provide suitable dynamic performance, with the initial design brief specifying a minimum target of 50 kJ for a 2.4 m bolt. Dynamic ground support performance is typically evaluated within the context of energy absorption capacity. Described simply, the method assumes a rockbolt absorbs the kinetic energy of an ejected rock mass as the rockbolt reacts force over some distance. If a moving rock mass has less energy than a bolt can dissipate, a rock ejection can be avoided (Li & Doucet 2011). Neglecting environmental losses, Equation 1 represents an approximation:

$$\frac{1}{2}mv^2 < f \times d \tag{1}$$

where:

m = mass of ejected rock.

v = velocity of ejected rock.

f = average force reaction of bolt.

d = distance over which the bolt force can react before failure.

Bolts are manufactured with each material and cut into 600 mm specimens. Each sample is pull tested to failure using a calibrated pull testing machine. The material's elongation capacities and their tensile strengths are measured and compared to evaluate their suitability. Testing revealed distinct characteristics between bolts made with material A and material B with some results presented in Table 1. Material A exhibited a higher elongation capacity, although it demonstrates a lower tensile strength than material B.

Table 1 Comparison of selected materials

Test	Peak load (kN)	Yield load (kN)	Peak/yield	Total elongation at maximum force (ISO 15630)*
'A' specification #1	333	241	1.38	10.9%
'A' specification #2	331	228	1.45	13.4%
'A' specification #3	338	223	1.51	12.4%
'B' specification #1	412	314	1.31	7.5%
'B' specification #2	411	300	1.37	6.1%
'B' specification #3	411	304	1.35	6.2%

*International Organization for Standardization (2019).

The Falcon Bolt relies on steel elongation to distribute force over a distance. The consistency of this mechanism depends on the regulation of steel properties and controlling how an encapsulation medium interacts with the bolt at different locations – both of which can be controlled. A greater elongation correlates to a greater energy absorption capacity, thus this method necessitates the use of a ductile material. However, suitability in static loading scenarios require the material to exhibit a stiff response. Stiffness and ductility are not properties that coexist in steels, and while mechanical design strategies could be implemented to achieve both conditions, this would certainly escalate production costs. To manage this compromise, two different

Falcon Bolt configurations are designed. The standard Falcon Bolt is developed to meet typical static load cases and will be manufactured using material B. A second dynamic configuration is developed that is fabricated with material A, since its greater elongation enables the target energy dissipation.

3.2 Short encapsulation pull testing

A short encapsulation pull test (SEPT) regime was conducted to determine the average bond shear strength between the encapsulation medium (resin/grout) and the threaded bar by analysing the static pull-out behaviour of the system (Hoien & Zhang 2021). Equation 2 provides a simplification of the interaction by neglecting bar and bore geometry, assuming *d* does not change during necking and neglecting the axial displacement of the bolt. Note the average shear stress is dependent on encapsulation length *L.* Therefore, there must be a length *L* where the bond shear strength is greater than the tensile strength of the bar, at which point the bar can be fully supported by the resin/grout. This point is the critical embedment length. This information is critical to the design process and from an implementation perspective, Hoien & Zhang (2021) note that the critical embedment length is an important parameter when deciding the length of grouted rockbolt required to support an unstable rock mass.

$$\tau = \frac{F}{\pi d \times L} \tag{2}$$

where:

τ = average shear stress.

F = applied load.

d = average bolt diameter.

L = encapsulation length.

The critical embedment length is determined for three of Jennmar's injectable encapsulation mediums: TD80 grout, JennThix resin (PUS) and J Lok P (polyester resin). A length of threaded bar is cut, and a portion of the bar is assembled within a steel tube of 51 mm internal diameter and a controlled length. The threaded bar is then injected with resin or grout, filling the steel tube and encapsulating the test length. After the medium has cured, the assembly is subjected to tensile loading until failure using a calibrated testing machine, and the load and failure mode are recorded. If the bolt pulls away from the encapsulation medium, it indicates that the length of encapsulation was insufficient to engage the bar. On the other hand, if the bolt breaks, it signifies that the critical embedment length has been met or exceeded. The experiment setup is demonstrated in Figure 3.

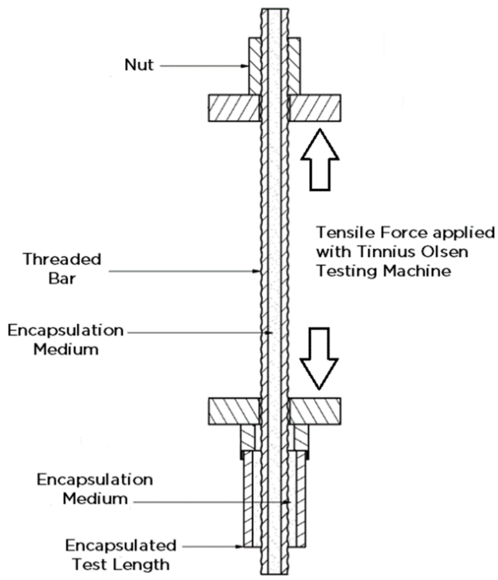

Figure 3 Short encapsulation pull test arrangement

Each medium is tested at 100, 300, 500 and 700 mm encapsulation lengths, with two tests performed for each length. A 24 hour curing time is selected, aiming to provide a benchmark comparison. Future work will include short encapsulation pull tests with resins after shorter cure times. Tests were consistent, and the averaged results are presented in Figure 4. 500 mm embedment was required to support the strength of the steel bar, with the critical embedment length expected to be within 400 and 500 mm. The critical embedment length for TD80 grout is anticipated to decrease as time passes and the grout cures.

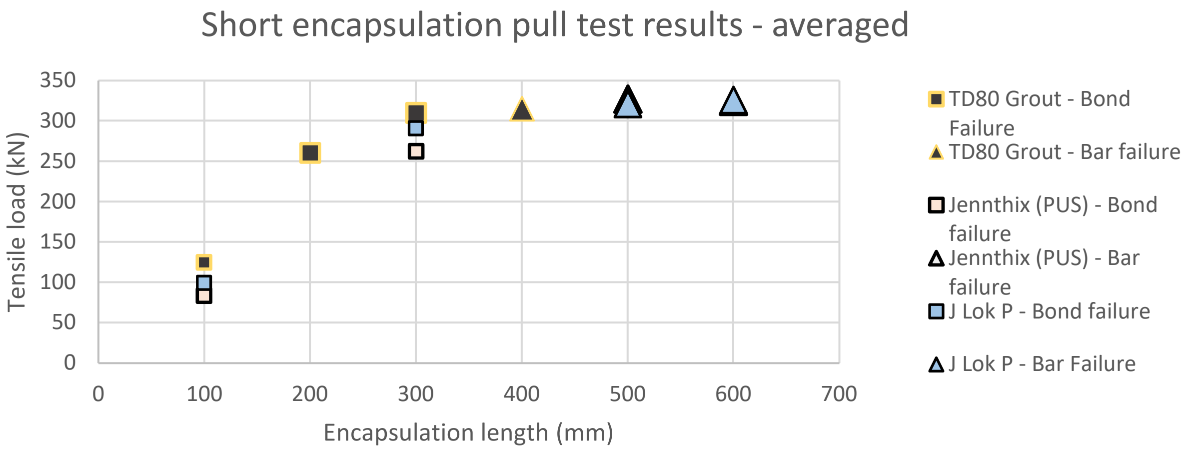

Figure 4 Short encapsulation pull test results

3.3 Mechanical anchor development

The initial design brief necessitated that the self-drilling bolt must be capable of pre-tensioning during installation. Multiple design iterations were undertaken to meet this objective without compromising cost feasibility. To evaluate each design iteration, a typical jumbo drill rig installed each prototype in concrete cylinders of 80–100 MPa, and a hydraulic ram pulled the tail of the bolt to determine the capacity of the anchor. Although concrete does not represent in situ mining conditions, these experiments offered a logistically feasible trial-and-error approach to refine the design. The testing aimed to determine if various prototypes met specific design criteria, including the ability of the shell to withstand the installation process, resistance to mesh interference, ensure bolt can pre-tension, and provide sufficient pull-out strength. Table 2 shows the results of one such experiment, comparing two completely different anchors, type A and B.

Table 2 Laboratory installation results from one initial trial

Sample	Expansion shell type	Equivalent drill rate (m/min)	Successful tensioning	Pre-tension (tonnes)	Pull test results	
					Tonnes	Comments
1	A	0.8	N	–	–	–
2	A	0.74	Y	2.74	6.1	Test stopped at 6 t to inspect shell
3	B	0.78	Y	1.63	4.9	Shell pulled free
4	B	0.77	Y	2.31	4.6	Shell pulled free
5	A	1.2	Y	2.43	20.6	Test stopped at 20 t
6	A	1.04	Y	2.32	12.2	Concrete cracked at 12 t
7	A	1.2	Y	2.04	20.2	Test stopped at 20 t

Eventually, a reliable, cost-effective expansion device was developed. Initial trials showed the anchor set could be easily engaged. However, the shell was found to be susceptible to inconsistencies during installation. These issues were managed with deliberate design decisions validated with further testing. Figure 5 shows a typical load and displacement relationship during pull tests on the final mechanical anchor. The tests show that in concrete, which is noted as being an unrealistic representation of mine conditions, the Falcon Bolt can consistently provide a 200 kN point anchor immediately after tensioning with no encapsulation. Section 4 presents results from in situ pull tests to show performance in different rock conditions.

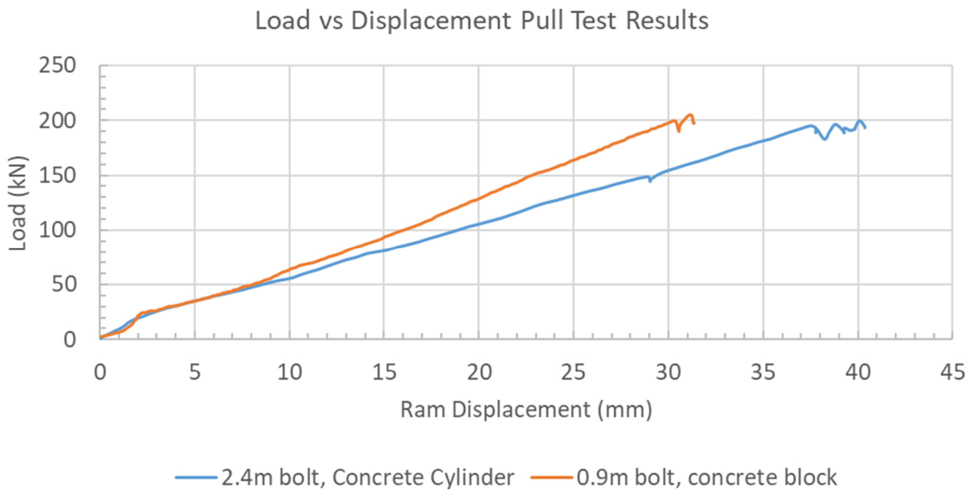

Figure 5 Load response of mechanical anchor

An experiment was conducted to establish a relationship between axial pre-tension and tightening torque. A Falcon Bolt was installed in concrete, and a load cell between the plate and the concrete block recorded axial force for a given tightening torque. Results are graphed in Figure 6. The peak tensioning torque was limited to 359 Nm due to available tools. However, modern drill rigs can output up to 625 Nm. Since the measured trend appears linear, extrapolation techniques are used to estimate that a modern jumbo could achieve 105 kN pre-tension if tensioned to stall, prior to resin injection. Further experiment is needed to confirm this estimation.

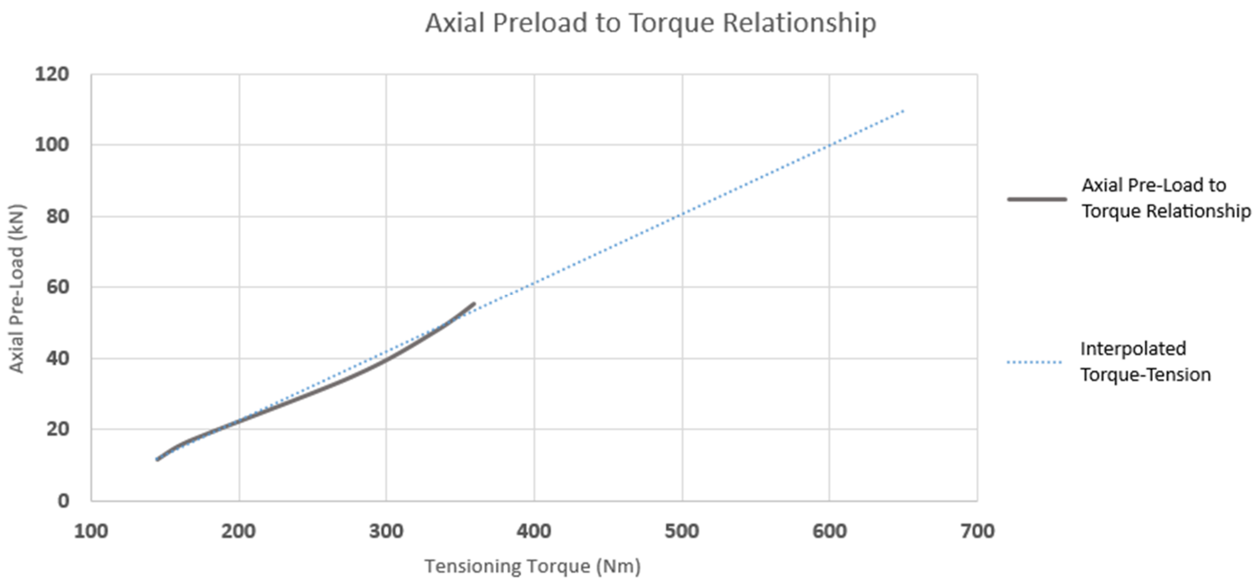

Figure 6 Axial preload to torque correlation

3.4 Influence of percussive drilling on mechanical properties of hollow bar

Abreu & Knox (2022) observed that the material used to manufacture a drill steel is typically optimised to transfer percussive power, while self-drilling bolts are generally engineered using ductile materials, providing the yielding mechanism that allows the bolt to perform in squeezing or seismic ground conditions. It was hypothesised that the ductile properties of the material could allow the bolt to be compromised during the installation process. Abreu & Knox (2022) then conducted an investigation to quantify the effect of the drilling process on the performance of a yielding self-drilling bolt when subjected to dynamic loading. The results of the investigation indicated that the installation process had a detrimental effect on the bolt's dynamic response, as evidenced by a reduction in average impact force, average elongation and average energy dissipation. To determine whether the Falcon Bolt may demonstrate similar behaviour, an experiment was conducted on two samples of R32 bar taken from the same batch of material. One sample was drilled into concrete and a second sample was retained as a control for comparison. Each sample was cut into three 800 mm sections and each was pull tested to failure. The load and elongation were recorded for each sample. See results in Table 3.

Table 3 Installed versus control group

	Total elongation at maximum force (ISO 15630)*	Max force (kN)
Control – sample 1	10.3%	321.71
Control – sample 2	10.7%	319.99
Control – sample 3	10.0%	315.16
Post installation – drive end	10.5%	323.30
Post installation – middle portion	11.6%	329.72
Post installation – toe end	11.5%	333.69

*International Organization for Standardization (2019).

The mechanical properties of the control bar and post-installation bar did not exhibit significant difference. The control bar does show a slightly lower average elongation and a slightly lower average force response compared to the post-installation bar. This may suggest some work hardening has occurred during installation – although, a larger sample size is needed to verify this, since this variance could be within the expected distribution for given batch of steel. The results from this test differ with the results found by Abreu & Knox (2022). However, the pull testing device used in this experiment pulls the bar to failure over two minutes, while the experiment conducted by Abreu & Knox (2022) used a drop tester, loading the bar within milliseconds. It is possible that the mechanical response of the bar has a time-dependent quality, and the difference between the work-hardened and raw bar may be more distinct if energy is applied at a higher rate (increased power).

The bar used in this experiment was installed into concrete cylinders while the bar used by Abreu & Knox (2022) was installed into quartzite. As a harder rock will impose a higher stress on a self-drilling bolt, it is feasible that the bar used in this experiment was not stressed to the same extent. Furthermore, this experiment used R32 bar with a yield strength of 315 kN, while Abreu & Knox (2022) used the BoraBolt manufactured with R28 bar and a yield strength of 200 kN. The R28 bar will see a higher stress for a given force since it has a smaller cross-section and will yield at a lower stress. The results of this experiment suggest that the Falcon Bolt's mechanical properties are not detrimentally impacted by the installation process. However, to confirm these findings, this experiment could be repeated with a larger sample size and the bolts could be drilled into harder rock. Additionally, a study may be conducted to observe how the mechanical reponse of a steel member is influenced by the rate it is worked.

3.5 Dynamic testing at Canmet

The dynamic capabilities of a given ground support element are becoming increasingly more important in the design of a ground support strategy, thus it is crucial the Falcon Bolt possesses dynamic response capacity. At the outset of the design process, it is agreed that the proposed 2.4 m self-drilling bolt must be capable of providing at least 50 kJ dynamic capacity, with steel yield as the chosen mechanism to dissipate energy, as described by Equation 1. The Falcon Bolt can be supplied with a systematically derived (see Section 3.2) 1,400 mm smooth de-bonded section along the middle portion of the bar. This prevents load transfer between the encapsulation medium and the bar. This smooth section is then free to yield during a dynamic loading event, while 500 mm of bar above the smooth section (bolt toe) grips to the encapsulation medium, anchoring it to a stable rock mass. To evaluate the effectiveness of this system, independent testing was completed by Canmet on five Falcon Bolt samples. The Canmet dynamic test rig simulates dynamic load scenarios by dropping a known mass over a selected distance onto a support tendon (bolt) in a simulated borehole. The Canmet dynamic test rig can drop a maximum mass of 3 tonnes from a height of 2 m, providing a maximum input energy of 58.9 kJ and a maximum velocity of 6.3 m/s. Loads are measured at the plate, with displacement measured at the plate and the toe (Plouffe et al. 2007).

Five 2.4 m samples were tested. Each sample is manually inserted in a pre-drilled 53 mm nominal diameter roughened borehole within two granite cylinders of uniaxial compressive strength (UCS) 130–145 MPa. Each completed test assembly then has two granite cylinders, with the split located 915 mm from the collar of the bolt. The separation of the granite cylinders represents a discontinuity in a supported rock mass. Each granite cylinder is fixed within a specially prepared steel tube, the same length as the individual granite cylinder, that applies an extremely stiff confinement element to the granite core. The test setup is demonstrated in Figure 7. After installation and tensioning to 350 Nm, 2.2 m of bolt engaged with the test cylinder with a 200 mm tail protruding outside. Each sample was then encapsulated with either J Lok P 1:1 (Jennmar's pumpable polyester resin), J Lok P 2:1 or JennThix PUS. Details and testing outcomes are reported in Table 4. Three samples were tested at 50 kJ input energy and two tests were performed at 30 kJ input energy. All tested bolts absorbed more than 50 kJ, with cumulative energy dissipation for 30 kJ tests approaching or exceeding 100 kJ. Kaiser et al. (1996) suggests 50 kJ per square metre as a performance target – a single 2.4 m Falcon Bolt installation surpasses this recommendation. Results from test sample 2 are presented in Figure 8. Test sample 2 absorbed two drops at 50 kJ, breaking on the second. On each test, the bolts failed in the de-bonded section in a 'cup and cone' profile, indicative of ductile failure under uniaxial loading. No deformation was observed on nuts, washers or plates.

The design methodology for the dynamic Falcon Bolt was successful, with each 2.4 m bolt consistently dissipating more than 50 kJ of energy encapsulated with Jennmar's pumpable resins. The theoretical framework utilised to select materials and determine the lengths of de-bonded and bonded segments has been experimentally validated, providing reassurance for its continued application in future design endeavours. Further work will include dynamic testing of the Falcon Bolt when encapsulated in grout, and study the dynamic response without an encapsulation medium to test the limits of the mechanical anchor set. With this data, it could be possible to develop a dynamically capable self-drilling bolt that does not require any encapsulation. Additionally, since the Falcon Bolt could not be broken in a single strike, the absolute dynamic capacity is unknown – only the cumulative capacity. In the future, it would be desirable to break the Falcon Bolt in a single strike.

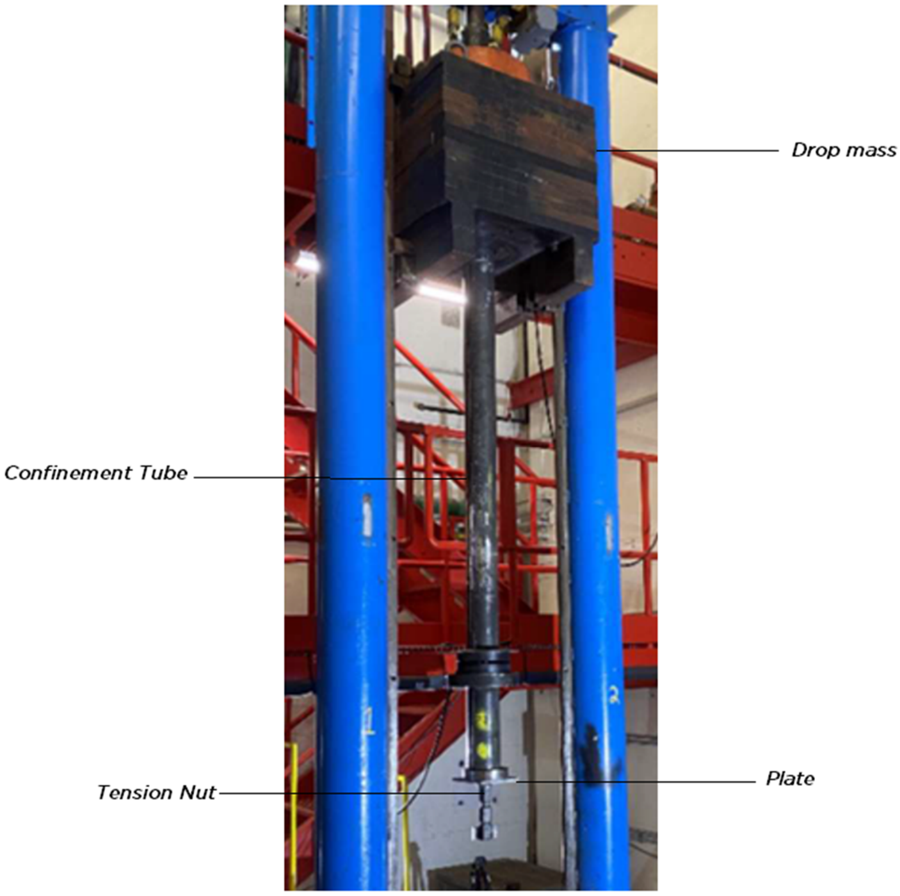

Figure 7 Dynamic test setup

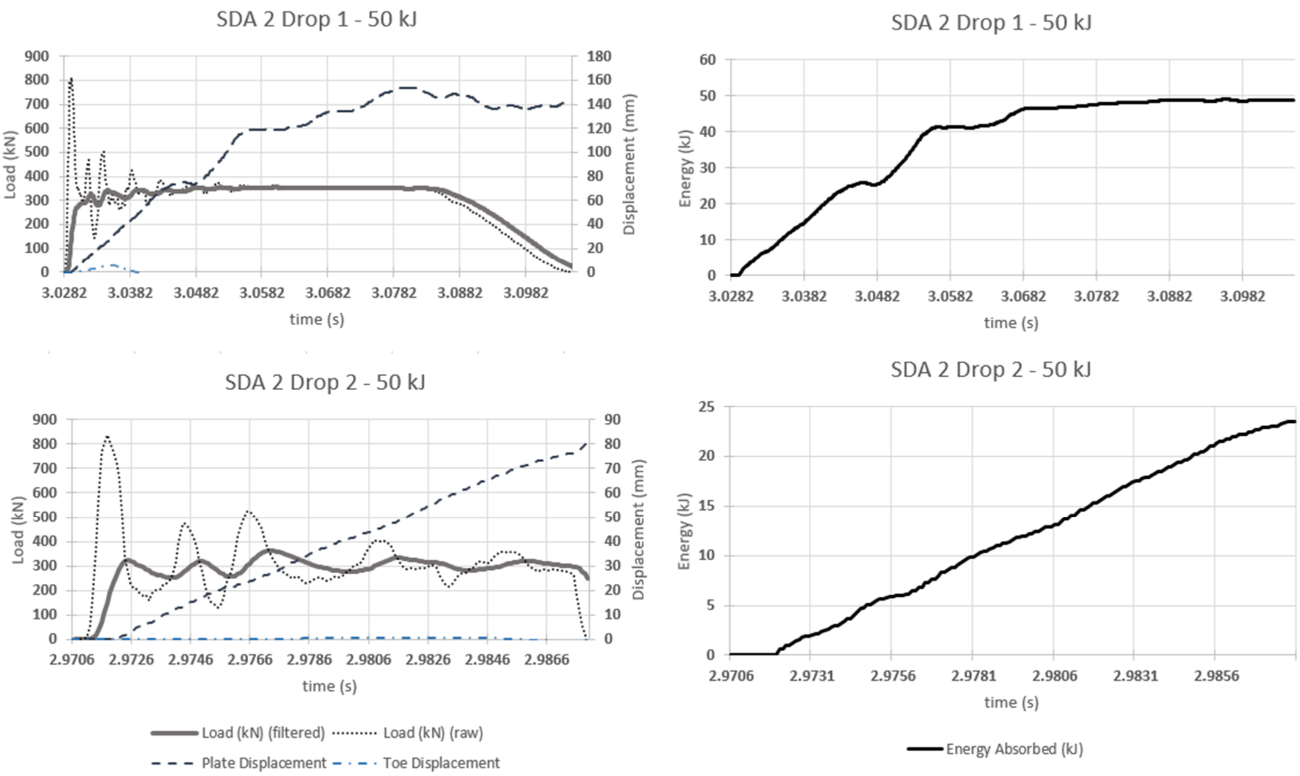

Figure 8 Falcon Bolt 2 dynamic test results

Table 4 Dynamic test results

Sample	Drop number	Encapsulation medium	Drop height (mm)	Nominal potential energy (kJ)	Plastic energy dissipated (kJ)	Cumulative energy at break (kJ)	Toe displacement (mm)	Plate displacement (mm)	Cumulative bolt elongation (mm)	Average impact load (kN)
1	1	J Lok P (2:1)	1,500	29.52	26.4	–	2.7	74.5	71.8	353.8
	2		1,500	29.52	27.4	–	0	73.8	145.6	371.7
	3		1,500	29.52	26.7	–	0	75.7	221.3	353.1
	4		1,500	29.52	22	102.5	3	74	292.3	297.8
2	1	J Lok P (2:1)	1,760	50.09	48.86	–	5.9	141	146.9	299.8
	2		1,764	50.14	23.52	72.38	0.5	82	229.6	302.3
3	1	J Lok P (2:1)	1,764	50.14	44.8	–	4.3	133	128.4	337.5
	2		1,756	49.91	22	66.8	2.7	71	196.7	310.3
4	1	JennThix PUS	1,500	29.52	27.7	–	2.7	66.9	64.2	414.3
	2		1,500	29.52	26.8	–	2.2	63.7	125.7	420.8
	3		1,500	29.52	26.7	–	1.8	63.1	187	423.6
	4		1,500	29.52	10.5	91.7	1.3	42.8	228.5	245.4
5	1	J Lok P (1:1)	1,859	52.84	50.6	–	0	129	129.4	390.8
	2		1,859	52.72	*	*	0	*	*	*

*Plate displacement measurement device failed during second drop.

4 Underground installation trials

Following the completion of laboratory trials, numerous underground installation trials were conducted aiming to evaluate the bolt's behaviour in a range of in situ conditions and obtain operator feedback. Overall, the implementation of the Falcon Bolt during these trials was successful. Although some minor concerns were identified, a systematic approach was employed to address and resolve these issues through the reiteration of the design phase.

Early trials involved the installations in fair to good rock mass (Q'10–15 and 80–120 MPa) with 3 m Falcon Bolts and extension-drilled 6 m bolts using two separate dollies. In this process, a first dolly is used to install the bolt, and a second dolly on the jumbo's second boom then tensions the Falcon Bolt. These initial trials aimed to verify basic performance characteristics including the ability to drill successfully in underground conditions, ensure the mechanical anchor can hold the bolt within the borehole prior to tensioning, and verify its suitability to function with existing installation equipment. Extension-drilled bolts were coupled successfully, and expansion shells held all bolts securely within their borehole prior to tensioning. The tensioning process was successful on every bolt trialled, however and some operators found the alignment of the tensioning dolly to be time-consuming. Accordingly, engineering modifications were implemented to the tensioning dolly to streamline this process. Further trials showed the modifications implemented on the dolly effectively improved the tensioning process, as indicated by positive operator feedback and reduced installation times.

Falcon bolts were also installed in extremely good ground conditions (Q' over 100), including dolerites of approximately 250 MPa to determine how the installation process can be affected by a different set of challenging conditions. The absence of any unusual wear on the drill bits retrieved from a 6 m borehole after installation confirms the ability of the drill in hard rock conditions, and successful tensioning showed that the anchor set can survive the installation process. Pull tests on the mechanical anchor prior to grouting showed that, in 250 MPa rock, the anchor was capable of reacting more than 250 kN and did not show any signs of disengaging. Drilling in harder ground subjected the drive components to higher and different loading conditions. Power transfer between the components was successful, although it was recommended that the material specifications of the drive components should be increased.

In trial B, three 6 m extension-drilled bolts were installed in ground conditions of approximately 250 MPa to determine how the installation process can be affected by challenging conditions and validate changes made to the tensioning dolly. The modifications implemented on the tensioning dolly improved the tensioning process, as indicated by positive operator feedback and reduced installation times. All 6 m bolts were installed and tensioned in under five minutes. In addition, the absence of any unusual wear on a drill bit retrieved from a 6 m borehole after installation confirms the ability of the drill bit in hard rock conditions. Pull tests showed that, in 250 MPa rock, the expansion shell was capable of reacting more than 250 kN and did not show any signs of disengaging. Drilling in harder ground subjected the drive components to higher loading conditions, but power transfer between the components was successful.

Further in situ installations were focused on trialling the single stage dolly and the grout injection procedure. The single stage dolly allows bolts to be installed and tensioned in the same process without the need to realign booms or change dollies. Each bolt was injected using a top-down encapsulation principle with Jennmar's TD80 grout or JennThix PUS. The single stage dolly had been successfully implemented in the laboratory. However, it was not known how this system would operate in situ. Through site trials and incorporating feedback from the experienced jumbo operators, the single stage dolly was modified and new centraliser bushings were manufactured to allow the system to function harmoniously. Initially, operators needed to adjust to the installation technique. However, once familiar with the system, average installation times decreased and operators commented on the potential to increase installation rates, particularly in challenging conditions. All bolts have been installed and grouted successfully with either a resin or cementitious grout and are currently fulfilling their ground support role. Results from trials are summarised in Table 5.

Table 5 Sample of data collected from a selection of installation trials

Rock type and quality (Q’)	UCS strength (MPa)	Average pre-grout anchor strength (kN)	Post-grout pull test (kN)	Average drilling rate (min/m)
Concrete cylinders – very good	80–100	204	>249	0.81
Mudstones, peppertites and faults – poor (1.7–4)	50–70	148	>249	0.76
Siltstones – fair to good (10–15)	80–100	>105	>249	0.75
Andesites, mudstones – good (20–30)	130–170	167	>249	0.83
Dolerite – extremely good (>100)	>250	>249	>249	0.93

5 Future work: large-scale trials

The aim of this design process is to develop a high-performance fully encapsulated bolt that offers increased installation efficiency compared to existing long-term support bolts. Figure 9 shows average Falcon Bolt installation times implemented with a mechanical resin injection system compared with data taken from internal time-in-motion studies for other bolt types. Figure 9 projects that the Falcon Bolt provides an increase in installation performance – particularly in poorer ground. A larger-scale trial needs to be undertaken comparing different bolt types to determine how this performance translates to overall gains in installation efficiency. Of particular interest are single heading development areas, where time is a critical factor, or mines with challenging conditions where low-cost friction bolts cannot be utilised due to their low strength, dependence on embedment length or susceptibility to corrosion.

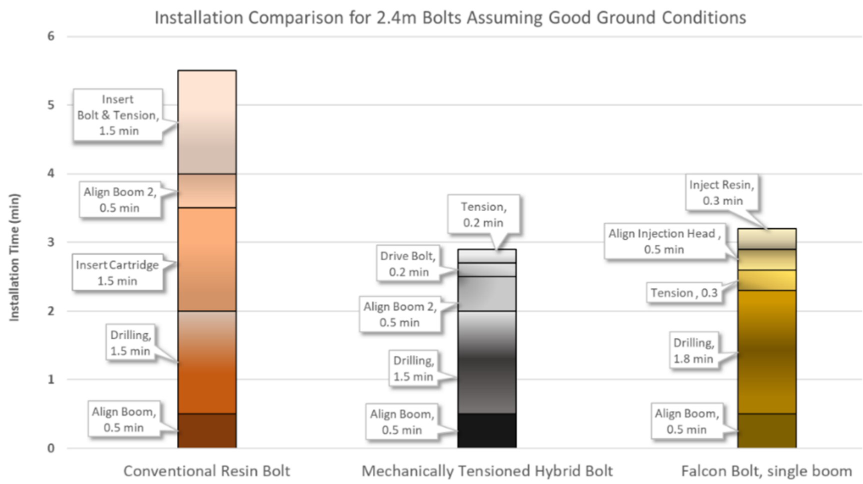

Figure 9 Comparison of installation procedures for different 2.4 m bolts

A brief analysis is prepared to predict the sensitivity of ground support installation cost to price per ground support unit (GSU) and time per installation. This analysis is used to estimate the advantage of the Falcon Bolt installation methodology compared to standard resin bolts. Equation 3 is developed to provide a simplified indication of the cost to install a GSU based on a set of assumptions, and neglects critical technical aspects such as quality of installation and specification of the GSU, project timelines or time value of money considerations. Table 6 presents the estimated cost sensitivity of an installation as a percentage increase or decrease relative to a base case, where the base case is a typical 2.4 m resin bolt.

$$C_{total} = C_{gsu} + t_{inst} \times C_{inst} \tag{3}$$

where:

C_{total} = cost to install GSU (AUD).

C_{gsu} = total cost for GSU (including resin, grout etc.) (AUD).

t_{inst} = average time per installation (mins).

C_{inst} = cost to operate installation equipment (AUD/min).

Assumptions:

- Base case is a 2.4 m resin bolt priced at 60 AUD per unit.
- Resin bolt is installed in 5.5 min if ground conditions are favourable.
- Cost to operate jumbo in ground support installation is AUD 2,500/h:
  - 10,000 AUD per cut. Two cuts per 10 hour shift – 2,000 AUD/h.
  - 500 AUD/h overhead operating costs.

Table 6 Projected cost sensitivity of ground support unit installation

			Time per installation (min)						
			-50% 2.8	-20% 4.4	-10% 5.0	0% 5.5	10% 6.1	20% 6.6	50% 8.3
Cost of ground support unit (AUD)	100%	120	-18.88%	4.90%	12.82%	20.75%	28.67%	**36.60%**	**60.37%**
	50%	90	-29.25%	-5.48%	2.45%	10.37%	18.30%	26.22%	**50.00%**
	20%	72	-35.48%	-11.70%	-3.78%	4.15%	12.07%	20.00%	**43.78%**
	10%	66	-37.55%	-13.78%	-5.85%	2.07%	10.00%	17.93%	**41.70%**
	0	60	-39.63%	-15.85%	-7.93%	%0	7.93%	15.85%	39.63%
	-10%	54	-41.70%	-17.93%	-10.00%	-2.07%	5.85%	13.78%	37.55%
	-20%	48	-43.78%	-20.00%	-12.07%	-4.15%	3.78%	11.70%	35.48%
	-50%	30	-50.00%	-26.22%	-18.30%	-10.37%	-2.45%	5.48%	29.25%

A trial could be conducted in cooperation with a mine to create a sufficiently comprehensive model. However, the estimation suggests that the overall cost of ground support installation is more sensitive to the time required per installation than to the individual cost per GSU. For example, the model predicts that a 10% decrease in GSU price correlates to an overall cost decrease of 2%, while a 10% decrease in time taken per installation correlates to a more substantial cost decrease of 7.9%. Given the pressure to decrease overall production costs through technological innovation, this observation can influence the way the industry considers ground support generally. Pursuing cheaper ground support approaches an asymptotic limit, beyond which corners are cut. If the industry shifts to pressure innovation on installation efficiency and installation quality control mechanisms, the gains in development rate, overall cost, safety and ground support quality could be far more significant. Table 7 presents an estimate on overall cost difference for the single boom installation of a Falcon Bolt, a conventional resin bolt and a typical mechanically tensioned hybrid type bolt based on Equation 3. According to the estimates, a 2.4 m Falcon Bolt, when utilised alongside a mechanical grout injection system, is expected to have a similar installation time as a hybrid type bolt, albeit the hybrid type bolt is cheaper per installation. However, the advantages of the Falcon Bolt, including its greater strength, higher dynamic capacity, versatility in challenging ground conditions and resistance to corrosion, position it competitively when the conditions become demanding. Additionally, since the Falcon Bolt installation can be completed with one boom and one dolly, cost per installation can be decreased further still. Time-in-motion studies will demonstrate the advantages of a twin-boom method, and site-specific comparisons can establish the gains in ground support installation efficiency for different conditions.

Table 7 Estimated cost comparison

	Installation time compared to resin bolt		Cost per installation compared to resin bolt
	min	%	%
Standard resin bolt	5.5	–	–
Falcon Bolt, single boom	3.2	-42%	-29%
Typical hybrid bolt	2.9	-47%	-37%

6 Conclusion

The Falcon Bolt represents a shift in design philosophy by aiming to provide an innovation on installation methodology. The ideological framework of the design rests on a search to find the most effective method to put the steel in the rock. Ground support installation has emerged as a focal point for improvement in the development process, and the Falcon Bolt has demonstrated its potential as a transformative innovation, offering enhanced bolting efficiency without compromising performance. Its increased bolting efficiency could correlate to a cost saving, since time incurs the greatest expense during ground support installation, and potentially increase development rates by decreasing time spent installing ground support between cuts. The experimental evaluation of the Falcon Bolt's mechanical point anchor has demonstrated its ability in a range of ground conditions, while the capability to provide immediate pre-tension enables novel ground support implementation strategies. The Falcon Bolt's static and dynamic capacity have been verified, with full capacity achieved after grout/resin encapsulation. Future efforts will focus on conducting large-scale underground trials to further validate its performance with a significant sample size. Additionally, further development will be dedicated to its integration with mechanical resin injection systems.

References

Abreu, R & Knox, G 2022, 'The influence of drilling on the performance of a yielding self-drilling rockbolt', in Y Potvin (ed.), *Caving 2022: Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 165–176, https://doi.org/10.36487/ACG_repo/2205_09

Bray, P, Johnsson, A & Schunnesson, H 2019, 'Rock reinforcement solutions case study: Malmberget iron ore mine, Sweden', in W Joughin (ed.), *Deep Mining 2019: Proceedings of the Ninth International Conference on Deep and High Stress Mining*, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 191–204, https://doi.org/10.36487/ACG_rep/1952_15_Bray

Canart, G, Kowalik, L, Moyo, M & Kumar Ray, R 2018, *Has Global Mining Productivity Reversed Course?*, viewed 6 September 2023, https://www.mckinsey.com/industries/metals-and-mining/our-insights/has-global-mining-productivity-reversed-course#

Humphreys, D 2019, 'Mining productivity and the fourth industrial revolution', *Mineral Economics*, vol. 33, pp. 115–125, https://doi.org/10.1007/s13563-019-00172-9

Hoien, AH, Li, C & Zhang, N 2021, 'Pull-out and critical embedment length of grouted rebar rock bolts – mechanisms when approaching and reaching the ultimate load', *Rock Mechanics and Rock Engineering*, vol. 54, pp. 1431–1447, https://doi.org/10.1007/s00603-020-02318-6

International Organization for Standardization 2019, *Steel for the Reinforcement and Prestressing of Concrete — Test Methods — Part 1: Reinforcing Bars, Rods and Wire (ISO 15630-1:2019)*, International Organization for Standardization, Geneva.

Kaiser, PK, McCreath, DR & Tennant, DD (eds) 1996, *Canadian Rockburst Support Handbook*, Geomechanics Research Centre, MIRARCO, Sudbury.

Li, C & Doucet, C 2011, 'Performance of D-bolts under dynamic loading', *Rock Mechanics and Rock Engineering*, vol. 45, no. 2, http://dx.doi.org/10.1007/s00603-011-0202-1

Plouffe, M, Anderson, T & Judge, K 2007, 'Rock bolts testing under dynamic conditions at Canmet-MMSL', *Proceedings of The 6th International Symposium on Ground Support in Mining and Civil Engineering Construction*, SAIMM, SANIRE and ISRM, Cape Town.

Türkmen, E 2009, *Mechanization and Automation of Rock Bolting in Mines*, master's thesis, Montan Universitat, Leoben.

Villaescusa, E, Varden, R & Hassell, R 2008, 'Quantifying the performance of resin anchored rock bolts in the Australian underground hard rock mining industry', *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, pp. 94–102.

Zheng, S & Bloch, H 2014, 'Australia's mining productivity decline: implications for MFP measurement', *Journal of Productivity Analysis*, vol. 41, no. 2, pp. 201–212.