Caving 2022 - Y Potvin (ed.)
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doi:10.36487/ACG_repo/2205_11

Performance investigation of the newly developed X-Plate

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Abstract

The decreasing availability of surface and shallow orebodies has driven an increase in the need for deep mining methods. One such method is cave mining, which has many advantages over other mining methods; however, these mines require a higher grade of ground support. Additionally, as a cave mine's production progresses, excavations are exposed to an increased likelihood of seismic events, which further emphasises the need for an effective ground support system design.

When designing ground support systems for cave mining, the rock plate plays an important role, particularly when considering dynamic ground support selection. In block caving mining operations, a rock plate that can withstand the stresses developed by the caving method is essential to ensure safety in the mine and access to drawpoints. Inappropriately selected rock-plates can collapse and push off the rockbolt head when exposed to high strata loads leaving the excavation not properly supported.

Recent years has seen a growth in testing methods to quantify the performance of new ground support components, allowing ground support suppliers to deliver products meeting the needs of high stress cave mining conditions. Laboratory dynamic testing apparatuses have provided the opportunity to quantify and qualify the performance of dynamic ground support elements, both as a system and as individual elements.

In order to improve product validation capabilities, and to better represent the loading scenarios experienced within caving mines, Sandvik developed a new laboratory dynamic test method that will be presented in this paper. This new test method provides dynamic loading conditions in a controlled laboratory setting, which compliments Sandvik's in situ dynamic test rig. The new laboratory dynamic test apparatus was utilised in the development of a new dynamic rock plate, to better complement the consistent dynamic performance of the MDX bolt. The new rock plate, the X-Plate, was developed to optimise material, dynamic energy capacity and subsequentially static compression capacity. When compared to the existing Sandvik rock plate, the X-Plate showed improvements of more than 54% in dynamic capacity and 22% in static capacity. In addition to the performance improvements of the X-Plate, a material reduction has resulted in a sustainability gain of an estimated 1,300 t CO_2 per year.

Keywords: *dynamic ground support, rock plate, bearing plate, dynamic testing, lab testing, sustainability*

1 Introduction

Mining in deep environments presents a special group of challenges, ranging from mining related stresses to miners' exposure to hostile work environments (Fairhurst 2017). These challenges drive mining companies, equipment suppliers and ground support suppliers toward continued research and development of innovative designs to improve the safety of deep mines and associated mining methods.

One area of deep mining which has become more popular is cave mining, which, through increased automation potential, is among one of the more economical methods to extract deep orebodies (Shekhar et al. 2019). Caving mines traditionally required long excavation life for ore extraction, which itself involves an extensive list of challenges. One particular challenge is optimising the ground support design in long life, high stress areas to ensure life of excavation is achieved while also remaining economical. In these areas, stresses and seismic events can lead to rockbursts, which can damage ground support. To meet such demands, the ground support scheme needs sufficient capacity, under both quasi-static and dynamic loading conditions. For a safe and efficient design, engineers must rely on information that suppliers provide with their products. While extensive efforts have been dedicated to defining the capacity of rockbolts, both in laboratory conditions (Vallati et al. 2020; Li et al. 2021) and in situ (Darlington et al. 2018), very little has been done to quantify the dynamic capacity of surface support. Tests have been conducted to quantify the capacity of rockbolt and mesh combination (Villaescusa et al. 2008) and shotcrete panels (Villaescusa et al. 2013). Typically, rock plates are statically loaded to define their capacity or rating (ASTM International 2019, F432–19) but, at current knowledge of the authors, no dynamic tests have been conducted to quantifying the performance of the rock plate alone.

In this space, Sandvik decided to quantify the capacity of their rock plate (BPG150650) by using newly developed laboratory drop testing equipment. This new test rig provides dynamic loading conditions in a controlled laboratory setting, which compliments Sandvik's in situ dynamic test rig.

The new laboratory dynamic test apparatus was also utilised in the development of a new dynamic rock plate, to better complement the consistent dynamic performance of the MDX bolt. The new rock plate, the X-Plate (BXPG150550), was developed to optimise material, dynamic energy capacity and subsequentially static compression capacity. When compared to the existing Sandvik rock plate, the X-Plate showed improvements of more than 54% in dynamic capacity and 22% in static capacity. In addition to the performance improvements of the X-Plate, a material reduction has resulted in a sustainability gain in the form of a CO_2 emissions reduction of up to 1,300 t CO_2 per year.

This paper will present a description of the new drop test method and the importance of dynamic testing during the development of the new rock plate. A collection of test results conducted on Sandvik's rock plates with the new rig will be reported to show the importance of a well-designed, high capacity, rock plate to mobilise the full dynamic capacity of a rockbolt.

2 Laboratory dynamic test facility

Hadjigeorgiou & Potvin (2008), outlined the four primary methods of dynamic testing; large-scale testing by controlled blasting, laboratory tests on core samples, passive monitoring with back-analysis of case studies, and drop test facilities that apply impact loads on reinforcement elements. However, in the 14 years since this publication, many new laboratory dynamic testing facilities have been constructed, to the point where most major ground support providers have in-house dynamic testing capabilities. These facilities utilise varying energy application methods, the two most popular are momentum transfer and direct impact methods (Li et al. 2021). The momentum transfer method is utilised solely in laboratory settings including SWERIM in Sweden (Vallati et al. 2020) and WASM in Australia (Player & Villaescusa 2004). Conversely, the direct impact method is used in both laboratory (Li et al. 2021) and in situ or field tests (Mikula & Brown 2018; Darlington et al. 2018). These two methods of energy application each have benefits and disadvantages, including applicability to the underground environment, ease of facility design, ease of data processing and time and costs associated with performing tests.

In an effort to increase Sandvik's R&D capability with testing existing and new products, particularly when considering dynamic loading scenarios, a new laboratory Dynamic test facility has been developed. This laboratory test facility provides opportunities to analyse the performance of ground support systems and elements when subjected to controlled dynamic loading. The Laboratory Dynamic Test Rig (LDTR) utilises the direct impact energy application method, which allows simple comparisons between results from Sandvik's in situ Dynamic Test Rig (iDTR).

With any dynamic testing method or facility, one of the key design features is the support frame stiffness. The support frame must be sufficiently stiff to minimise energy loss through deflection of the frame. With this in mind, the frame for the LDTR was designed to be as stiff as possible, whilst still creating an easily operable test rig and cost-effective construction. The LDTR has been designed to apply a dynamic energy up to 47 kJ in a single impact, with a drop mass of 2,541 kg and an impact velocity of 6.1 m/s.

The test consists of a known mass falling from a set height to impact a plate directly connected to the lower part of the reinforcement bar (Figure 1), which acts as a guide for the free-falling mass. The impact energy is transferred from the plate to the fixed end (top of LDTR frame) through the re-bar, where elongation and plate deformation dissipate the applied energy. The input energy is defined as the sum of two components: the kinetic energy at the impact, plus the extra energy introduced during the elongation of the sample. This latter component is neglected in the calculation of input energy, as different bolts have different response to the dynamic input and only the impact energy should be used when comparing different bolts (Li & Doucet 2011). The magnitude of the applied energy is derived using the energy conservation law and is equivalent to the product of the drop mass, gravitational acceleration, and the free-fall height.

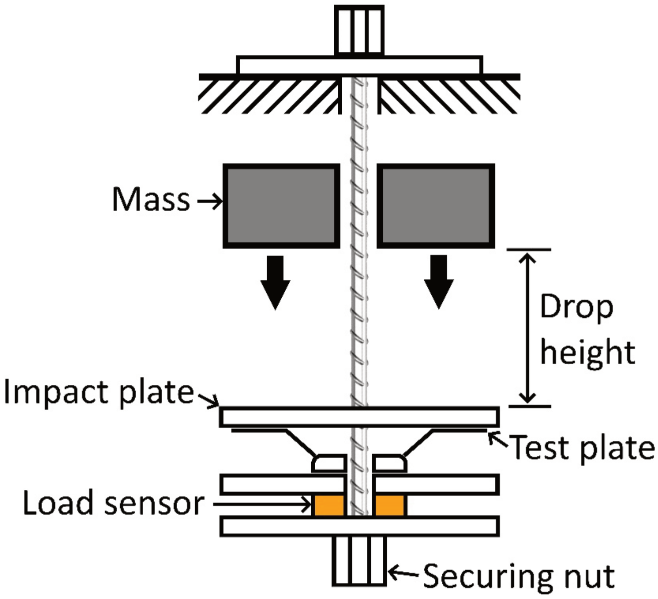

Figure 1 Laboratory dynamic test rig arrangement

The energy absorbed by the sample is calculated by integrating the load displacement curve derived from the sensors. The impact load is directly measured by a hollow piezoelectric loadcell, which is located directly in the load path. The displacement is extrapolated from a high-speed camera recording with use of image analysis software, which tracks targets attached to the test rig and specimen through the test. The load displacement curve is consequently created by synchronising the two sensors and finally analysed on a spreadsheet.

The LDTR is remotely controlled for safe operation. Two lifting magnets are used to raise the drop mass to the desired height, which are controlled with a remote pendant, allowing the operator to fire the test from a safe distance, as shown in Figure 2.

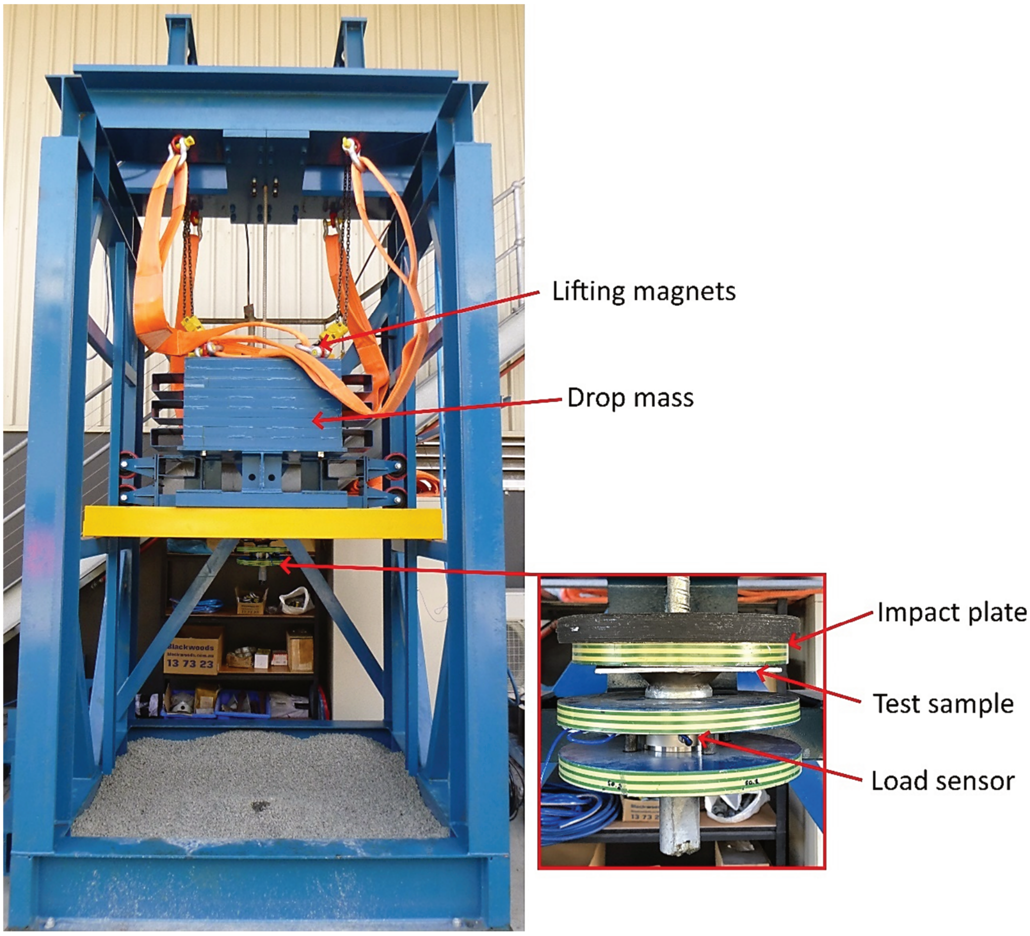

Figure 2 Laboratory dynamic test rig; detail of magnets, loadcell and rock plate

3 Dynamic rock plate development

New dynamic ground support elements traditionally undergo a rigorous test regime to establish the products' performance when tested under both static and dynamic loading scenarios. This is particularly important for rock plates, which transfer the rock load from surface support to the rockbolt. If a rock plate is not designed to withstand particular loading conditions, the chance of the rock plate failing is significantly increased. This is of particular concern when considering the design requirements of a caving mine.

Some of the major ground support design requirements of a caving mine include excavation life, static load capacity, dynamic load capacity, and the interaction between surface support and rockbolt. When considering the rock plate, load capacity, both static and dynamic, are possibly the most important considerations. As without a suitable load capacity, the rock plate can collapse prematurely resulting in an insufficiently supported excavation.

When designing new rock plates numerous aspects should be considered including shape, sizing, material grade, fit with other ground support products, static load capacity and dynamic energy capacity. When the X-Plate was in development, these aspects were critically reviewed to ensure the X-Plate would meet all requirements from manufacturing to mine application. The first aspect of the design was to determine the required static load capacity and dynamic energy capacity. These requirements would then drive many of the other factors including shape, size, and material. An additional requirement for the X-Plate was to reduce the material thickness, which promised to provide a sustainability improvement for the new product.

The existing rock plate (BPG150650) has been utilised with the MD bolt since 2010 and has an excellent track record. However, with the introduction of the MDX bolt with a consistently high dynamic performance, the dynamic performance of the existing rock plate was largely unknown. The existing rock plate is manufactured from 6 mm thick HA250 material (250 MPa yield strength) and is 150 mm × 150 mm; however, the plate is typically used in a combi-plate configuration whereby the rock plate is welded to a larger thinner plate. This configuration is used in many market areas, as it provides an improved connection between the rockbolt and surface support.

Before development work commenced on the X-Plate, the existing rock plate performance was established to act as a benchmark, and to quantify the improvements of the new plate. This benchmark consisted of a historical review of static compression testing of the rock plate (BPG150550) along with a series of static tests in Sandvik's Bolting and Cutting R&D laboratory, located in Heatherbrae, Australia. The static testing was conducted using a support platen with a Ø70 mm through hole, a radiused washer and a load control rate of 5 mm/min, with the results from the static capacity review shown in Table 1 and Figure 3. These test results show some variability between production batches; however, the historical minimum will be used as the benchmark.

Table 1 Rock plate static benchmark

Test source	Test ID	Peak load (kN)	Compression at peak load (mm)
Historical minimum*	BPG150650-prod	219	14.6
Lab test sample 1	BPG150650–1	233	17.8
Lab test sample 2	BPG150650–2	243	16.4

* Historical minimum based on 24 months of data – 36 samples.

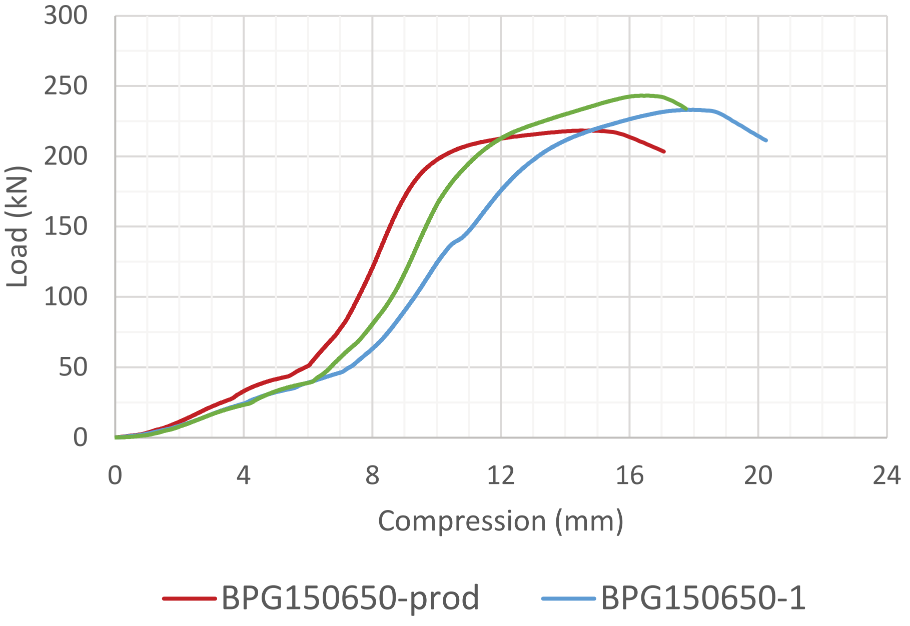

Figure 3 Rock plate static test benchmark summary

Along with static testing, dynamic testing was conducted to establish the maximum dynamic energy the existing rock plate could withstand in a single impact without collapse. This testing utilised the newly developed LDTR, where each plate sample was tested with a new re-bar extracted from a Sandvik MDX bolt from the same production batch, ensuring re-bar performances were comparable. The testing regime found the maximum energy capacity of the BPG150650 rock plate to be 28 kJ. When tested with an impact energy of 30 kJ, the rock plate collapsed, with the test parameters shown in Table 2 and load displacement response shown in Figure 4. The displacement shown in Figure 4 includes the elongation of the re-bar, which does assist in dissipating the dynamic energy.

Table 2 Rock plate dynamic test parameters

Sample	Test ID	Theoretical impact velocity (m/s)	Theoretical Impact energy (kJ)	Total input energy (kJ)*	Peak load (kN)	Absorbed Energy (kJ)**	Energy absorbed by bar only (kJ)	Peak system displacement (mm)	Final system displacement (mm)	Final Bar displacement (mm)	Final Plate compression (mm)
BPG150650–28	20201207–1	4.7	28.1	31.9	255	34.1	32.5	152	141	127	11.4
BPG150650–30	20201207–3	4.9	30.1	34.1	258	34.8	32.8	163	149.5	129	18.73**

* Total input energy includes the potential energy at the point of impact and the additional energy applied through the displacement of the bar and plate.

** The energy absorbed includes the plate energy absorption through plate compression and bar energy through bar elongation.

*** Plate collapsed.

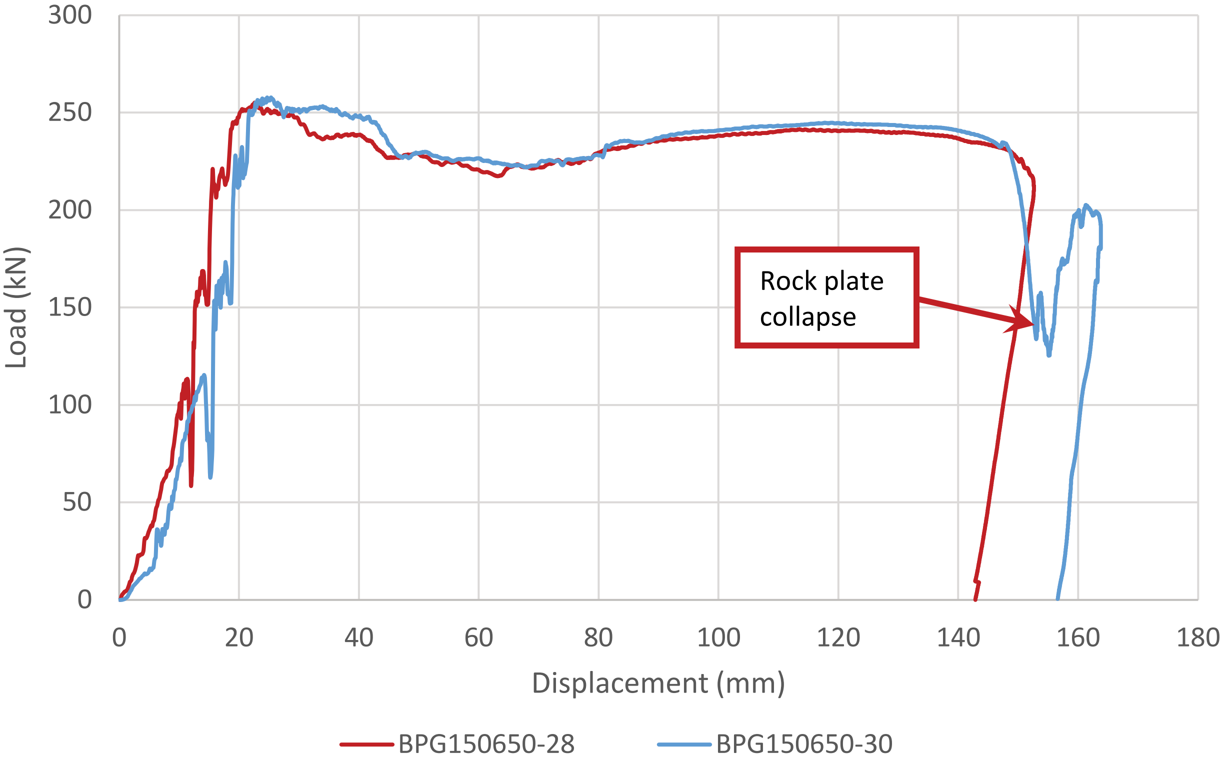

Figure 4 Rock plate BPG150650 dynamic load displacement response

This benchmark data was crucial to identify not only the load and energy capacity of the existing rock plate, but also the failure mode. The failure mode of the existing rock plate was similar in both static and dynamic testing, which was partial flattening of the central domed section and lifting of the outer corners of the base, as shown in Figure 5.

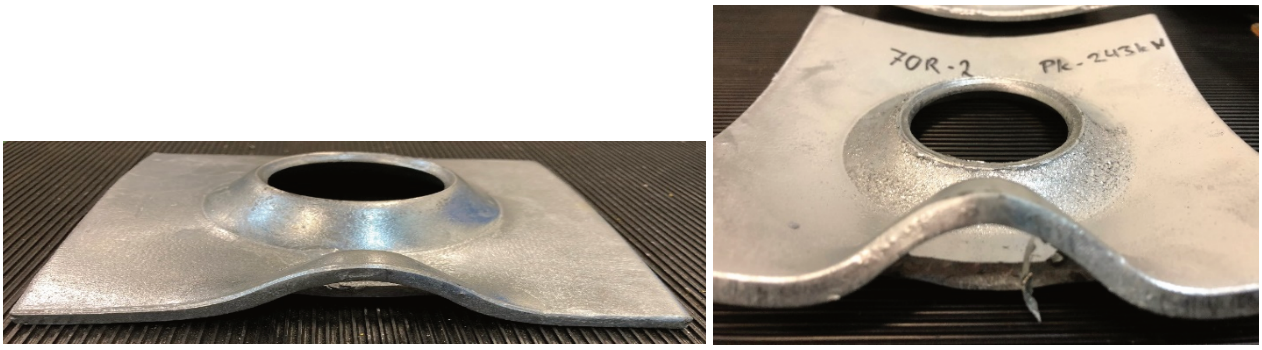

Figure 5 Rock plate (BPG150650) before (left) and after (right) static compression test

Based on the failure mode of the existing rock plate, if the central dome strength in increased, the static capacity of the rock plate would subsequently increase. Several methods were tested to increasing the central dome strength included additional material on the domed section, modified dome geometry and ribs around the dome. One of the key criteria in selecting the dome strengthening method was to minimise any changes in manufacturing methods and eliminate any additional production processes. The design which proved to increase the strength of the central dome with no change to manufacturing method, and no additional manufacturing processes, was to introduce radial ribs into the domed section.

These ribs were selected to form an X-shape, aligning with the diagonal corners of the plate, to potentially increase the stiffness of the corners of the plates, as illustrated in Figure 6. This additional stiffness was anticipated to prevent the corners of the X-Plate from lifting during loading, which would further strengthen the X-Plate.

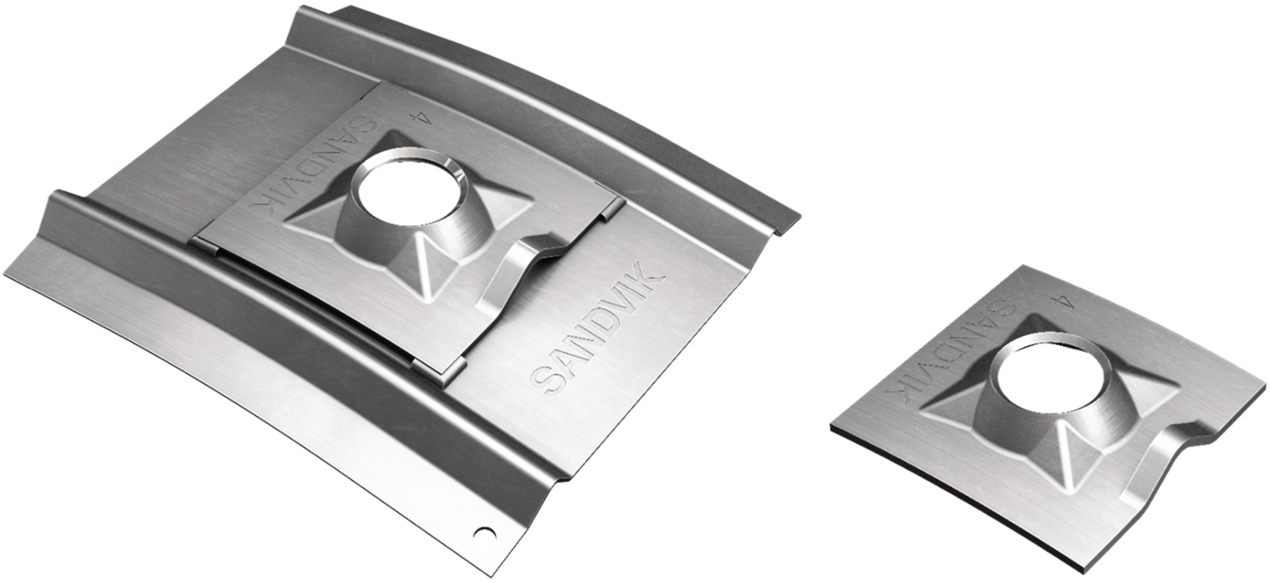

Figure 6 Overview of newly developed X-Plate. Left: X-combi-plate (BXPG3002805); Right: X-Plate (BXPG150550)

Material thickness for the X-Plate prototypes initially started at 4.0 mm in HA250 material to establish the strength variation with the estimated minimum material thickness. However, the test results were far below those of the existing plate, which was also the case for prototypes in 5 mm HA250 material. Therefore, 5 mm HA350 material prototypes were tested, which proved to be the successful design, surpassing the static capacity, and far exceeding the dynamic capacity of the existing plate. The static performance was increased by approximately 22% and the dynamic capacity by more than 54%, as shown in Table 3, Figure 7, Table 4, and Figure 8.

Table 3 X-Plate static performance test results

Test source	Test ID	Peak load (kN)	Compression at peak load (mm)
Historical minimum	BPG150650-prod	219	14.6
X-plate sample 1	BXPG150550–1	297	13.1
X-plate sample 2	BXPG150550–2	267	13.4

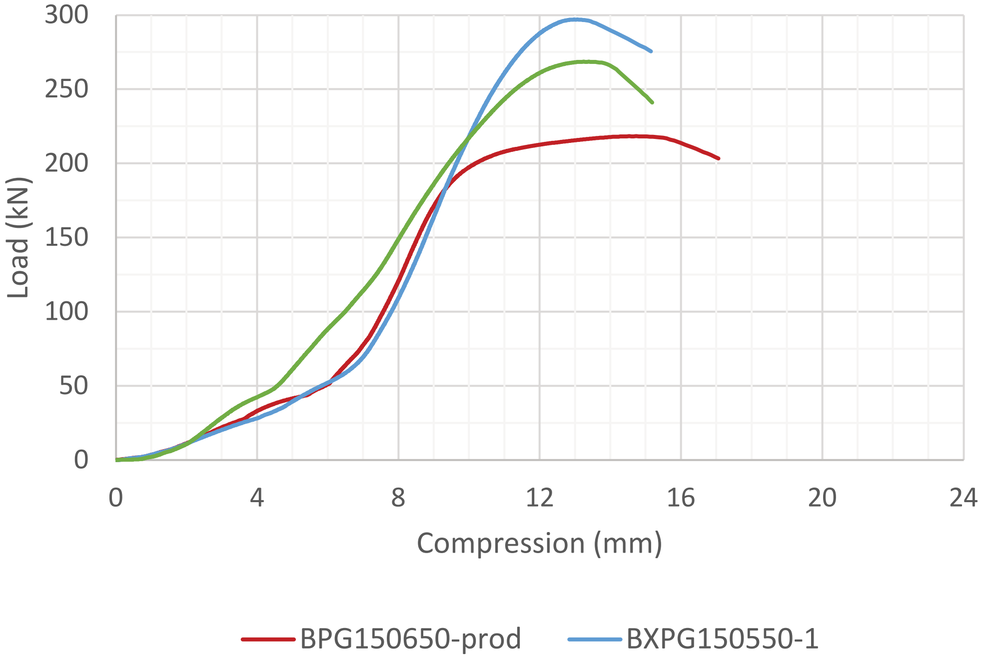

Figure 7 X-Plate comparative static performance

Table 4 X-Plate dynamic test parameters

Sample	Test ID	Theoretical impact velocity (m/s)	Theoretical Impact energy (kJ)	Total input energy ** (kJ)	Peak load (kN)	Absorbed Energy (kJ)*	Energy absorbed by bar only (kJ)	Peak system displacement (mm)	Final system displacement (mm)	Final Bar displacement (mm)	Final Plate compression (mm)
BPG150650–30	20201207–3	4.9	30.1	34.1	258	34.8	32.8	163	149.5	129	18.73***
BS-865–5-350–30	20201207–4	4.9	30.1	33.9	270	34.9	34.1	152.7	145	135	6.9
BXPG150550–43	210412–2	5.8	43.1	48.5	271	49.5	48.6	223	210	202	7.1

* The energy absorbed includes the plate energy absorption through plate compression and bar energy through bar elongation.

** Total input energy includes the potential energy at the point of impact and the additional energy applied through the displacement of the bar and plate.

*** Plate collapsed.

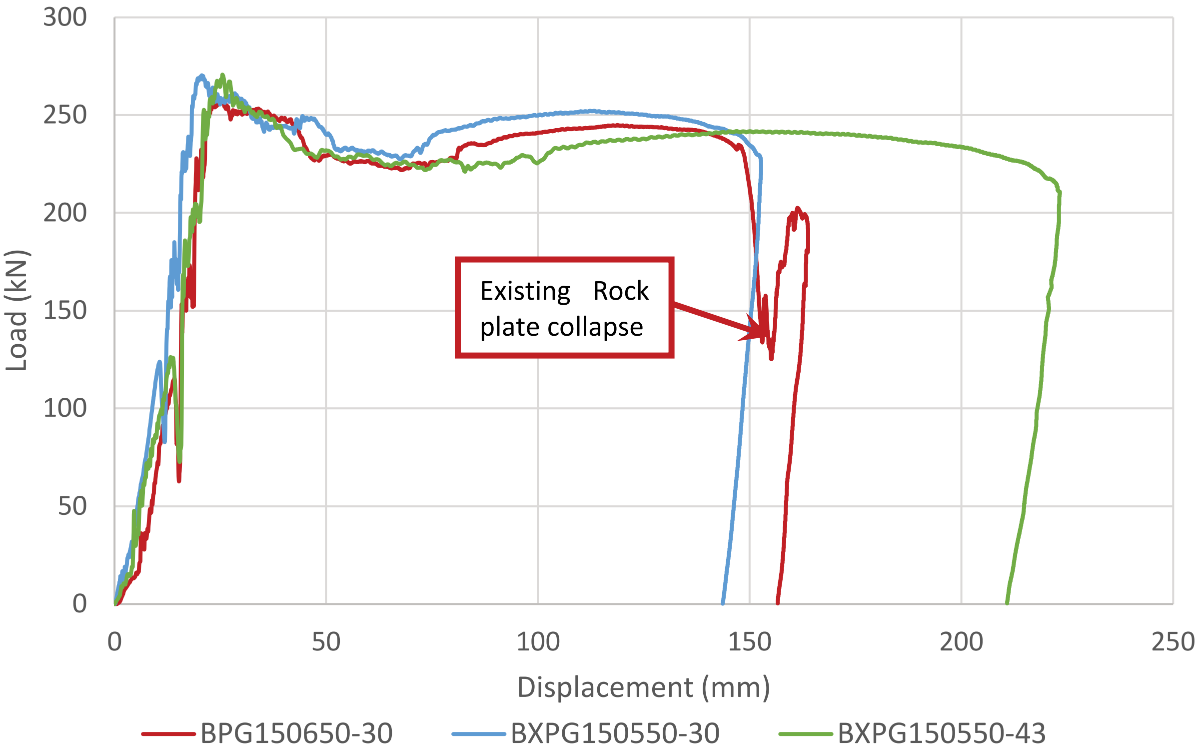

Figure 8 **X-Plate dynamic load response**

As shown in Figure 8, the X-Plate far exceeded the dynamic capacity of the existing rock plate, with a successful result when subjected to a single impact of 43 kJ. A total of six tests were conducted with a single impact of 43 kJ, which confirm these results with minimal variation. When viewing the sample post-test, there are insignificant signs of any damage, as shown in Figures 9 and 10, the only visible change is the compression of the slight bow in the base of the plate.

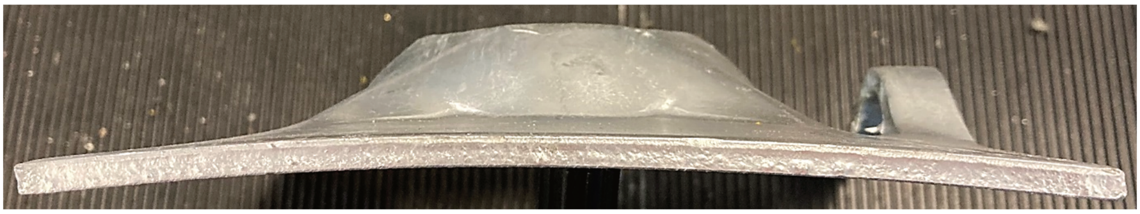

Figure 9 **X-Plate before dynamic test**

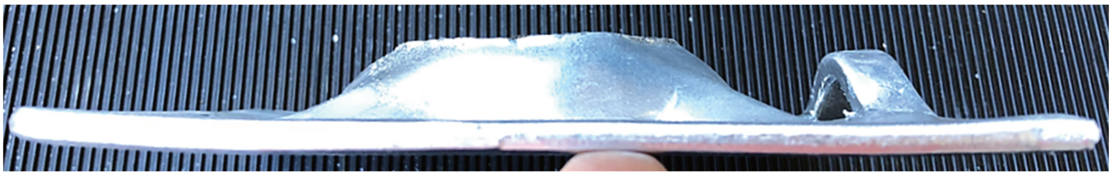

Figure 10 **X-Plate after 43 kJ dynamic test**

Based on these results, the X-Plate has an improved static and dynamic capacity of 22% and 54% respectively, when compared to the standard rock plate.

With an ever increasing focus on the environment and sustainability, the X-Plate had a secondary design goal to reduce the material thickness. This reduction in material thickness reduces the weight of steel required to manufacture the plate and reduces the mass of the plate for transportation. Sandvik has established standard CO_2 emission levels through various aspects of a products life and utilising these values an estimated reduction in CO_2 emissions can be calculated. During production, the reduction in CO_2 emission is estimated to be up to 1,284 t CO_2, with an additionally 9 t CO_2 during transportation. These values allow not only Sandvik, but the customer to know that steps are being implemented to reduce the impact of the production of mining consumables on the environment.

4 Conclusion

Caving mines often present high stress environments, which can increase the demands on operations, miners, machinery, and ground support designs. These high stress environments provide opportunities for continuous improvements in designs of machinery and consumables. One particularly important area is the capacity of ground support elements, which geotechnical engineers rely on ground support suppliers to provide accurate information on component strengths and capacities.

In this light, Sandvik successfully developed a new laboratory dynamic testing apparatus, which was utilised to quantify the performance of the existing rock plate (BPG150650) and to develop a new X-Plate (BXPG150550). The new X-Plate far exceeded the performance of the existing rock plate with an increase in static and dynamic capacity of 22% and 54% respectively.

The X-Plate improved capacity allows full utilisation of both the static and dynamic capacity of the MDX bolt, which has shown consistent dynamic performance during in situ testing. This knowledge will allow mine planners and excavation designers to have full confidence in the products used in the ground support design, enabling support designs that meet the high stress and economical requirements of a caving mine.

Acknowledgement

The authors acknowledge the collaborative efforts provided by the Sandvik Bolting & Cutting Research and Development and product management teams through not only the design and commissioning of the laboratory dynamic test apparatus, but also through the many steps to develop the X-Plate.

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