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# A review of the interaction between the surface and deep elements of ground support leading to design guidelines of a holistic ground support approach in mining

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## Abstract

*Ground support systems consist of surface support that contacts the excavation boundary and a reinforcement system that is embedded into the rock mass. The demand on the components depends on the expected loading conditions from the ground and the type of excavation, being of construction or civil type or rather of mining extraction. The application of ground support materials and methodology is often adapted to meet technical requirements and economics, but this marriage of reason sometimes leads to less-than-optimal configurations. A review of the combination of existing bolts and accessories from the industry suggested that some design considerations seemed to be overlooked.*

*This paper presents the results of an investigation into the overall behaviour of combined bolt and bearing plate elements and the design process that can lead to an optimal support system that is able to handle various loading types from quasi-static to dynamic events. Practical engineering considerations, as well as past and new laboratory data, are presented and discussed. Based on several years of laboratory testing and field applications, the data explores the choice of accessories with various bolt types and strengths, offering a simple approach to quantify the parameters to properly design the ground support system.*

**Keywords:** *plates, ground support, system, rebars*

## 1 Introduction

Face plates, or washer plates, are usually the main part of surface load transfer of tendons used in rock stabilisation. Although the continuous interaction between the grouting material or the tube surface and the rock mass is the acting principle of grouted or friction reinforcement devices, a large part of the excavation stability is due to the face plate's capability to sustain the load and deformation of the rock mass upon it and to keep the mesh and other surface support functioning properly. Louchnikov et al. (2014) have identified that a conservative approach to surface support should consider 70% of the dynamic energy to be handled by the surface support (mesh, shotcrete, plates). It is therefore critical that the face plates are able to sustain the energy transmitted to them, slowly or rapidly, for the surface support to work adequately.

Face plates come in various sizes, shapes and strengths. Figure 1 shows three types of face plates used extensively in underground mining. For those types, the surface, thickness, strength, and hole diameter can vary widely to accommodate bolt and nut diameters.

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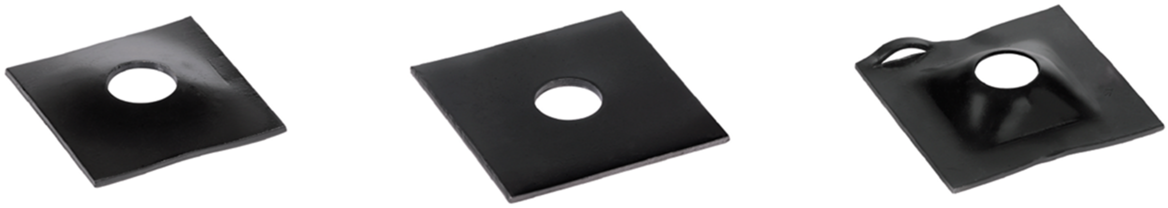


**Figure 1 Three basic type of face plates used in underground excavations: domed plate, flat plate, and friction bolt plate**

The tendons' surface control effectiveness is influenced by the washer plate used with them. The selection of that critical link needs to follow some rules to allow the system to function correctly. To perform this combination adequately, we must consider both the mechanical behaviour of the tendons and the plate. Also, it is critically important to consider the application context of the ground support system. In conditions where the ground conditions are completely known and controlled, the design can be based on the elastic range of the ground support: yield strength and tensile strength. However, in more variable conditions, as often encountered in deep and high-stress mines, the loading conditions can suddenly exceed the static limits established for the ground support; hence, a more adaptable approach is needed, and the face plates are the key to this adaptability.

## 2 Mechanical properties of rockbolts

The mode of loading that links the tendons and the face plates is the tensile loading. A simple method used to provide engineers with the mechanical boundaries of applicability of a given tendon is a tensile test, either performed at the laboratory or in the field. The laboratory method mimics the field application where one end of the tendon is held stable and the other end – usually the part that will be outside the ground – is pulled out by means of a threaded pull adapter or a moving plate. The yield load and the tensile load (ultimate) are recorded for the rockbolt. These values will vary according to the steel strength and bolt cross-section. The length of the specimen will affect only the elongation and not the strength parameters.

Ground support suppliers provide tendons by classes of material strength with standardised diameters. Table 1 shows the steel specifications of the rockbolts most used in North America. For threaded products, the values are provided for the standard peeled and rolled threads method which provide a minimum performance level used in most design applications.

**Table 1 Mechanical properties of typical rebars used as rockbolts in mining**

| Specifications – forged head rebar | Yield load (min) | | Tensile load (min) | | Elongation (min) |
|---|---|---|---|---|---|
| #6 (3/4") Gr 60 | 26,400 lb-f | 117 kN | 39,600 lb-f | 176 kN | 8% |
| 20 mm Gr 60 | 29,000 lb-f | 129 kN | 43,500 lb-f | 194 kN | 8% |
| #7 (7/8") Gr 60 | 36,000 lb-f | 160 kN | 54,000 lb-f | 240 kN | 8% |

| Specifications – threaded tension rebar | Yield load (min) | | Tensile strength (min) | | Elongation (min) |
|---|---|---|---|---|---|
| #6 (3/4") Gr 60 | 20,000 lb-f | 89 kN | 30,100 lb-f | 134 kN | 8% |
| 20 mm Gr 60 | 22,000 lb-f | 98 kN | 32,000 lb-f | 142 kN | 7% |
| #7 (7/8") Gr 60 | 27,700 lb-f | 123 kN | 41,600 lb-f | 185 kN | 8% |
| 22 mm Gr 60 | 28,000 lb-f | 125 kN | 42,000 lb-f | 187 kN | 8% |

# 3 Mechanical properties of face plates

Face plates have mechanical properties that are controlled by their shape and thickness. Modern steels and stamping practices allow the use of thinner coil material to achieve their rated capacity.

One of the most used ratings for plate capacity is the ASTM F432 Standard (ASTM International 2019) which defines the grade of face plates based on the minimum load achieved in steps of 44.5 kN (10,000 lb-f) for a deformation of 6.4 mm (0.25 in) between 26.7 kN (6,000 lb-f) and the rated capacity. For example, a Grade 2 plate will provide a minimum of 89 kN (20,000 lb-f or 10 US tons) before a displacement of 0.25 inch (6.4 mm) between the range of 26.7 kN (6,000 lb-f) and 89 kN (20,000 lb-f). A Grade 3 domed plate will provide a minimum of 133.5 kN (30,000 lb-f) during the same deformation criterion.

The ASTM F432 Standard does not use the ultimate load value and in fact only provides incomplete information about the minimum value of plate strength. In that sense, the ASTM grading system can only be used in conditions of elastic loading of the rockbolt and the plate is considered as a static accessory that must be stronger than the load design of the bolt. The bolt is then left to do its work within its designed bearing load. If conditions occur that lead to excessive loading of the bolt, then failure will happen unexpectedly with heads becoming projectiles (e.g. Thomas 2015), leading to potential instability, ground failure, and safety issues for the operation.

It is also interesting to consider the shape of a domed plate. It offers some deformability compared to a flat plate, but once it is totally collapsed, it works effectively like a flat plate. Its stiffness is a function of the dome steepness, the material thickness, and the stamping process. A typical Grade 3 domed plate load-deformation curve is shown in Figure 2. This plate is typical of Grade 3 plates delivered on the Canadian market. In this case, the plate can sustain up to 158 kN (35,500 lb-f) with a deformation pattern that fits the requirement for an ASTM Grade 3 face plate. However, if one uses the ASTM grading system, this plate could also meet the lesser Grade 2 rating.

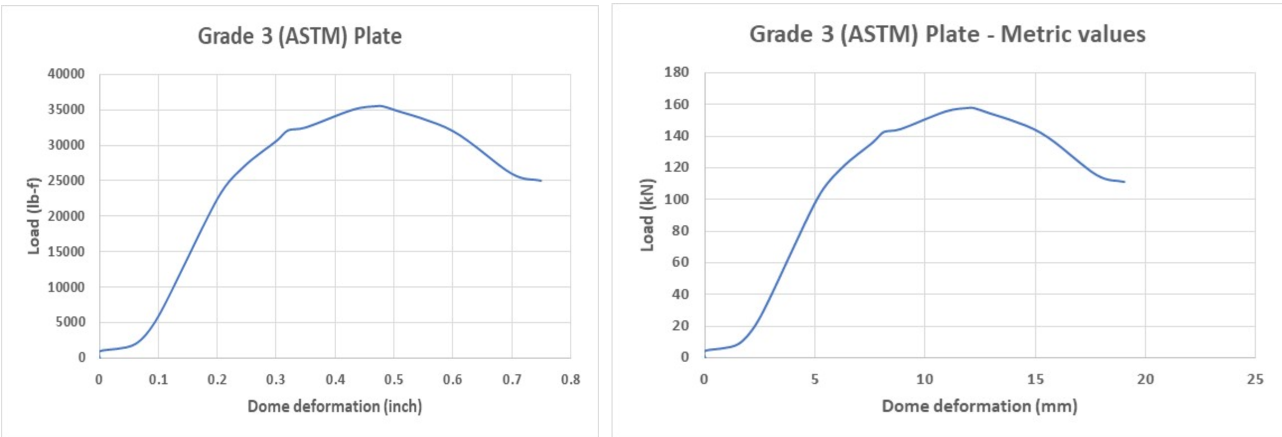



**Figure 2 Complete load-deformation of a Grade 3 domed plate used in mining applications in Canada**

# 4 Interaction between bolt and plate

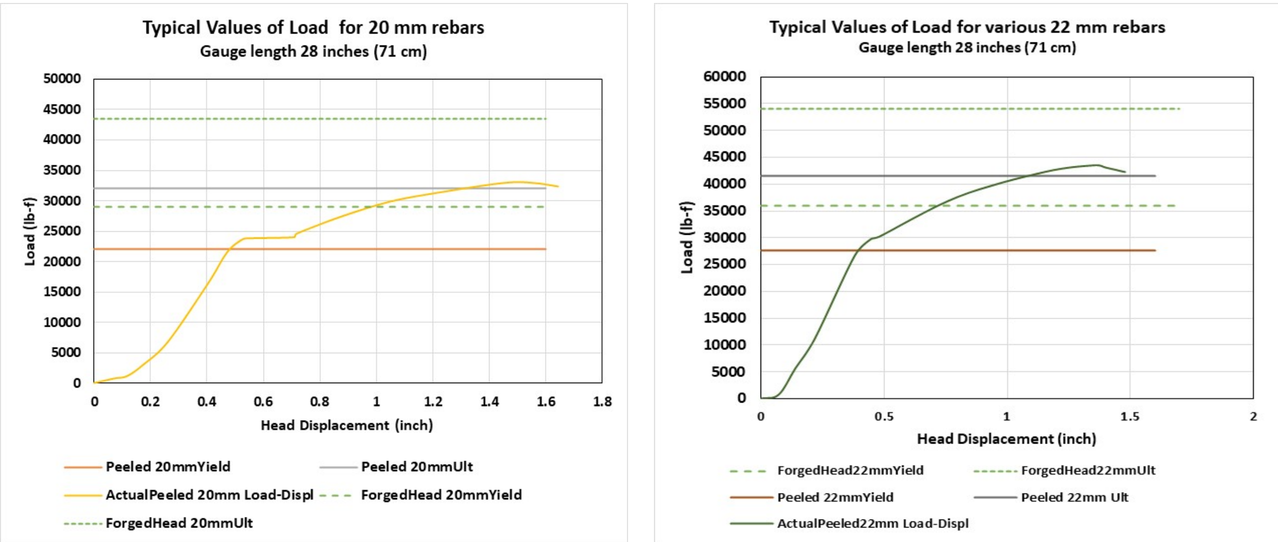
Over the last decade, the use of domed face plates has become commonplace, not only because they provide a better adjustment for uneven rock faces encountered in hard rock mining but also because they provide some cushioning for the rockbolt head and can warn the operator that the bolt plate array is close to the limit of its designed life. The dampening effect of the face plate in a dynamic environment has been discussed previously (Charette & Bennett 2017) and the choice of the plate influences the holistic performance of the system to a large extent.

To be able to use the domed plate as an efficient warning system and a damping device, one must select a plate that matches the mechanical properties of the rockbolt used. The analysis needs to be conducted on a quasi-static case first to ensure that the basic design of the support system will work at its base level.

## 4.1 Quasi-static loading conditions

Figure 3a shows the typical load-displacement curve of a 20 mm Grade 60 rebar compared with the published yield and ultimate (tensile) load for similar rebars and forged head rebars. Figure 3b shows the same information for 22 mm diameter rebars. If the loading is done at the laboratory with a longer bar or in the field with a short length of steel exposed out of the ground, the tensile failure of a threaded rebar is likely going to occur at the threads. The failure of the forged head rebar will occur between the head and the location of the next peak load of the bar.

For 20 mm rebars, if the bolt is designed to work up to the yield load, then for totally static conditions, the plate minimum capacity should be above 89 kN (22,000 lb-f) for threaded bars and above 129 kN (29,000 lb-f) for forged head bars. For the same loading conditions with the 22 mm rebars, the plate capacity should be above 125 kN (28,000 lb-f) for the threaded rebar and 160 kN (36,000 lb-f) for the forged head rebar.




(a) (b)

**Figure 3 Typical load-deformation curves for peeled and rolled threaded rebars, and typical yield and tensile load values for threaded rebars and forged head rebars. (a) 20 mm bars; (b) 22 mm bars**

It is important to understand that if the capacity of the plate is below the yield load of the bolt, the plate will show signs of overstress and collapse before the bolt has reached its yield load which creates an alert situation where no risk is present yet. This indicates that a well-designed plate can be used as a monitoring mechanism for the support system.

## 4.2 Yielding and dynamic loading conditions

In mining environments where the conditions are such that designing for achieving static loading conditions would be non-economical, the engineer has to use the tendency of the rock to self-support and enhance the conditions leading to that natural stability. In order to achieve this stable condition, the support system needs to be adaptable to higher deformation than elastic strains and be resilient enough to reach that level of deformation without failure to the bolt, plate, mesh or other support elements like shotcrete. This is valid for slow convergence situations but also for seismically active areas and rockbursting conditions.

It is also instructive to consider the case where the definitions of the loading conditions are not well known so the real static loading might exceed what was predicted by numerical modeling, for example. In that case, if the plate is stronger than the tensile capacity of the bolt used, the failure will be sudden and without warning. There could therefore be a serious risk for the operators and the equipment and an unfortunate increase in mining costs due to rehabilitation and scheduling issues.

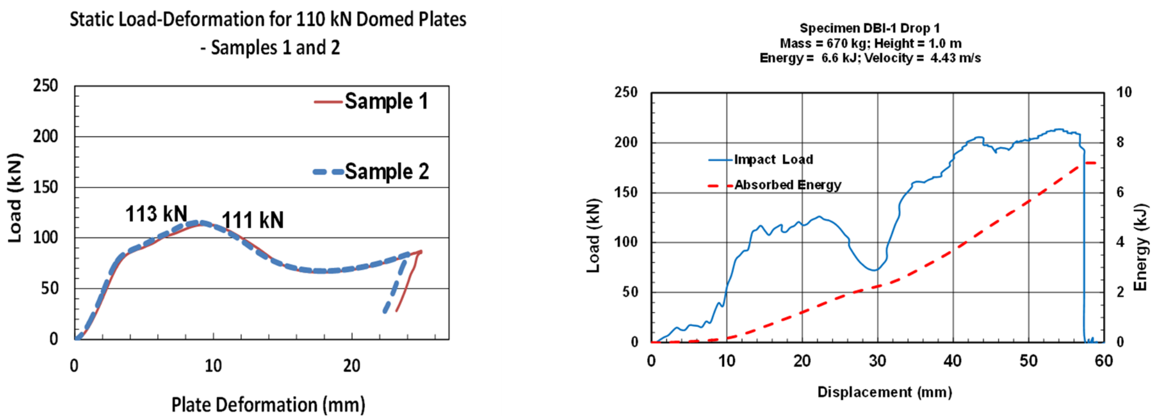
### *4.2.1 Yielding ground, high stress, and convergence*

With the threaded rebars, the correct range of plate strength that should be used to provide a good load transfer and a warning in case of high loading and convergence can be evaluated using Figure 3. From Figures 3a and b, it is possible to determine the suggested plate load capacity to be used with peeled and rolled threaded rebars, as well as with forged head rebars, for 20 and 22 mm diameter bolts. While a very specific collapse load value would be more elegant, it is more practical to use a range for the collapse load as it is not commercially viable to target a very exact collapse value due to the variability of steel properties and stamping processes, even in the same steel type and grade. We are suggesting to use a reasonable manufacturing range of 8,000 lbs (+/- 4,000 lb-f or +/- 18 kN) to meet the loading need in slow deformation conditions. This range follows roughly the basic ASTM grading; the graph was kept in imperial units to better draw a parallel with the ASTM system. The suggested range for 20 mm threaded rebars would be between 98 and 133.5 kN (22,000 and 30,000 lb-f), and 133.5 to 169 kN (30,000 to 38,000 lb-f) for 22 mm threaded rebars. These suggested ranges would not be high enough to serve as load indicators with the forged head bolts

The analysis performed for the rebar can be done with other types of ground support like expandable rockbolts, expansion shell rockbolts, cable bolts, etc. Thompson & Villaescusa (2014) provided a good testing strategy for various bolt types. What needs to be known is the yield and tensile strength of the head of the bolt, which is the weakest point of most bolts, in order to compare with the plate loading limit.

### *4.2.2 Dynamic conditions, high stress, and convergence*

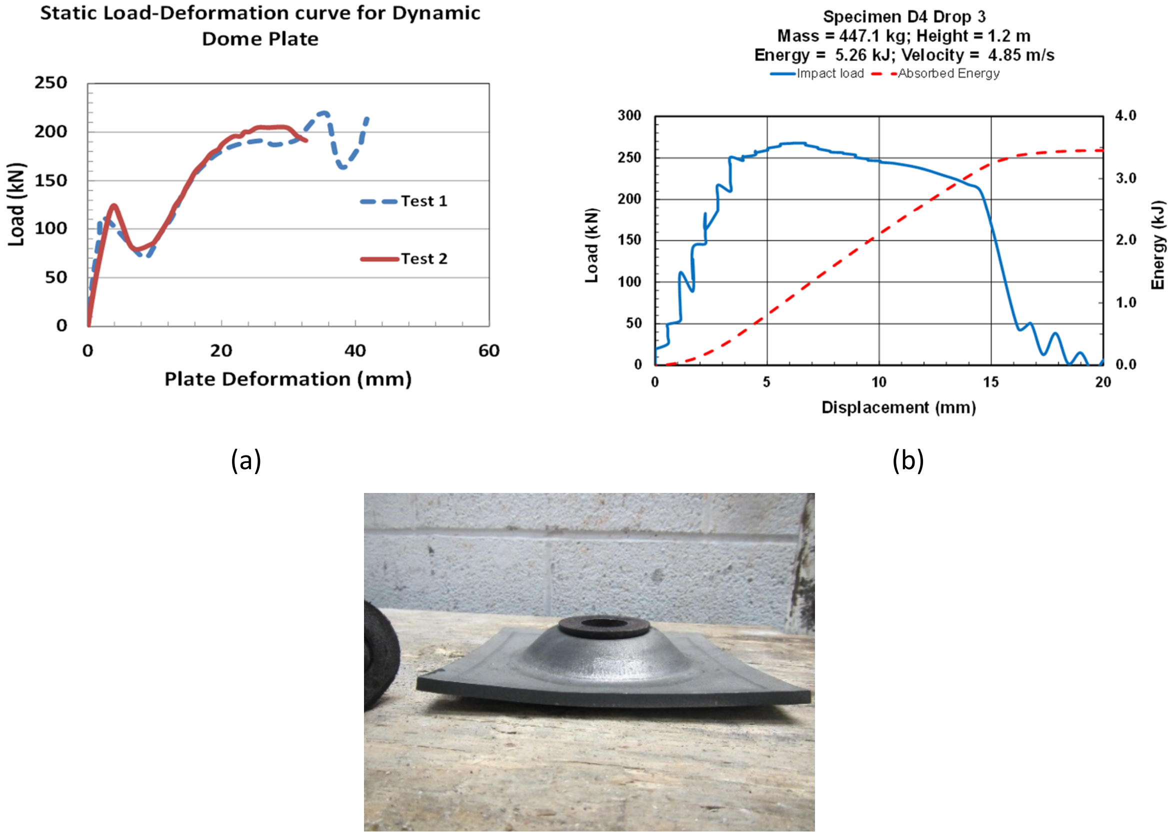
The inadequacy of the terminating elements (face plates, etc.) on the dynamic performance of the ground support system has been shown to reduce the available mechanical capability of the tendons as retainement support (Ortlepp 2001; Ortlepp & Stacey 1997; Ortlepp et al. 1998). A laboratory experiment performed in 2014 (Charette et al. 2014) provided some insights on the quantitative impact on the tendon performance. The test used a dynamic rockbolt (D-Bolt) used with a soft domed plate (Figure 4) and a strong domed plate (Figure 5) at the same level of dynamic loading. The results highlighted the significant impact on the energy damping capability at the collar of the bolt used in the test. The strong plate provided a better damping ability than the soft one which led to premature failure of the bolt at the threads. This effect would be seen with rebars as well since it affected mostly the head area of the bolt (D-Bolt tested by continuous tube method in this case) and it would likely be the same with a fully grouted rebar, albeit with less deformation. It is postulated that the strong plate acts like a spring and dissipates a sizeable amount of impact energy by mechanical and frictional energy compared to the soft plate that rapidly collapses and offers very little energy dissipation.




(a) (b)

**Figure 4 Results of low impact drop test with a low strength domed face plate. (a) Static test on the low strength domed plate; (b) First and last drop test with low strength domed plate (107 kN / 12 US tons) and dynamic rockbolt (from Charette et al. 2014)**

The quantitative impact of the face plate on the bolt performance is not well defined yet, and more extensive testing should be conducted to better understand the energy dissipation mechanism and the strength requirements for the plates used with different rockbolts in dynamic conditions.




(a) (b)

(c)

**Figure 5 End results of low impact dynamic test using strong face plate. (a) Static test on the face plate; (b) Last drop test (third) to failure at cumulative 14 kJ energy dissipation with a dynamic rockbolt and 178 kN (20 US tons) capacity domed plate; (c) State of the plate after the third drop (from Charette et al. 2014)**

## 5 Impact of the hole diameter

A critical parameter in the selection of the plate is to ensure that the nut will not pass through the hole of the plate, whatever the loading conditions. There is a trend in the mining industry to try to minimise the number of different face plates used in a single operation, to simplify inventory and reduce mistakes due to confusion over what plate goes with a given bolt. The potential problem with this approach is to undermine the performance of the plates by increasing the hole diameter to fit several rockbolt types. A larger hole diameter can reduce the capacity of a dome plate and it can lead to the nut pulling through the hole of the face plate if the plate is not strong enough to handle the load.

So it would be advisable to always perform an extended collapse test like the one shown in Figure 6 for nut/hole combination that are going to be used by the operation. This particular test was done with a high domed plate (volcano style) and a 22 mm rebar with a spherical seat nut. As seen on that graph, the nut is still hanging over the hole even when the plate is completely folded over, proving that the plate can take the full load of the bolt and more. Another important observation is that the plate folds over only after the ultimate load of the plate has been exceeded. In that case, the plate was loaded past 178 kN (20 US tons) and as the dome collapsed, the retaining load went down and the sides went up at 151 kN (17 US tons) or less. This softening behaviour is welcome as it will allow additional deformation during the final deformation that serves as a warning phase.

Figure 7 shows the condition of a strong 178 kN (20 US tons) capacity domed plate before and after two drop tests. The plate is flattened at the first drop and continues to work like a flat plate after the second drop. Its condition is very similar to the conditions observed at the end of the post-collapse test and the static test can be a first step for determining if a plate will survive a dynamic situation.

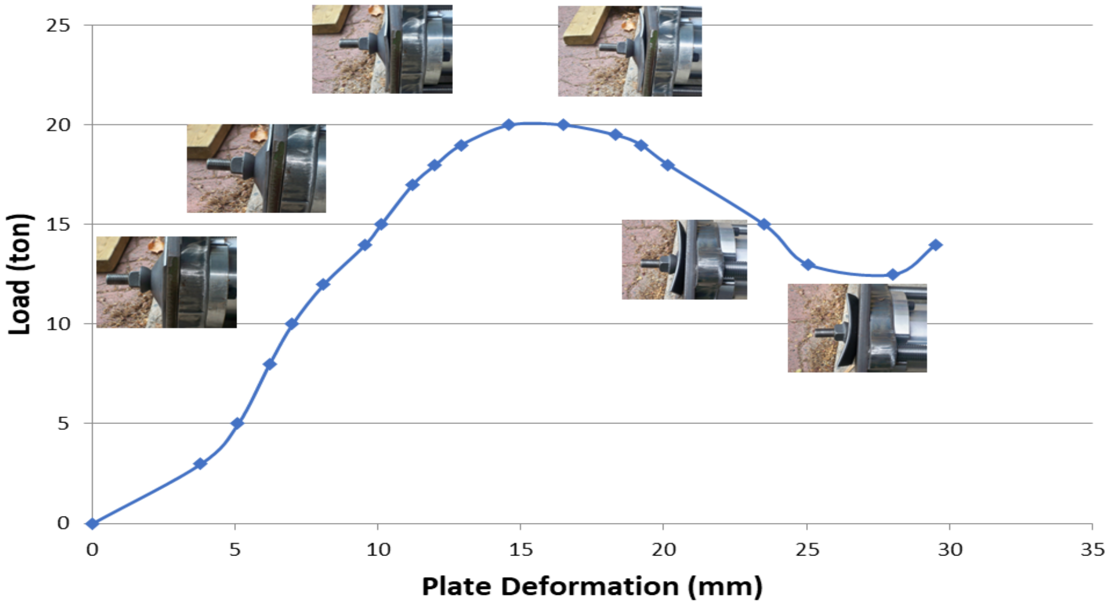
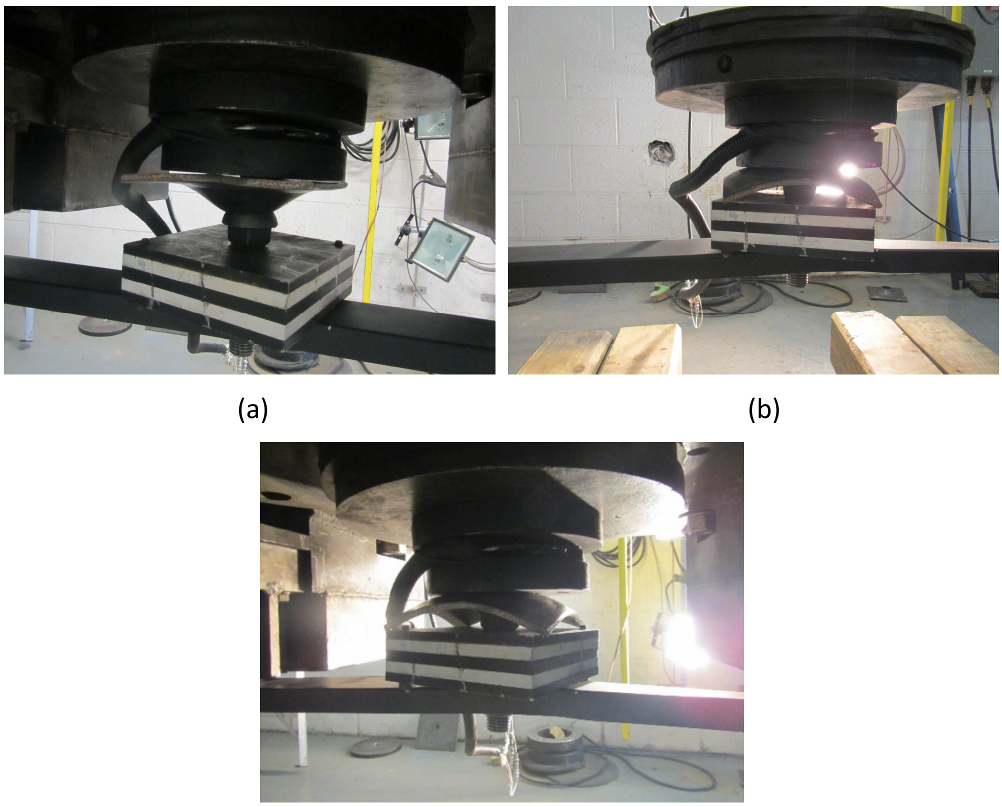



**Figure 6 Complete load-deformation curve of a domed plate loaded to a full collapse with the appearance of the face plate at each deformation stage**



(a) (b)

(c)

**Figure 7 Condition of a 178-kN (20 US tons) capacity domed plate during a drop test (a) before a 20-kJ drop, (b) after a first 20-kJ drop and (c) after a second 20-kJ drop test (Charette & Bennett 2017)**

## 6 Discussion

The assessment was conducted for rebars and one type of domed plate. However, the engineer should have the results of an extended collapse test at their disposal to be fully aware of the performance of the combination bolt plate. The exercise needs to be repeated for all bolts and plates used in the ground support system.

A simple procedure is suggested to provide an engineered selection of the duo bolt plate array:

- Perform a tensile loading of the rockbolt without the plate to determine the intrinsic characteristics of the load-deformation curve of the bolt. This should be done in the laboratory and in the field to have a better understanding of the behaviour of the bolt.
- Perform a tensile test of the rockbolt with the plate chosen to be used with the bolt. Special attention must be taken to define the plate thickness, hole diameter, dome height, grade of the plate or load rating. The test must be conducted to the complete collapse of the dome, if applicable, and up to the unfolding of the plate to verify how secure is the nut versus the hole.
- The test can be conducted for different plate thickness and hole diameter, if needed, and a production sample of the chosen plate should be tested. This would satisfy the static, quasi-static and yielding ground design.
- If the ground conditions are expected to trend toward actual seismicity, it should be evaluated if the plate can handle the dynamic impacts. It is suggested that if the plate passed the static testing, it should be tested with the bolt in dynamic loading (like a drop test) to address the capability to survive dynamic conditions and allow the bolt to perform to its designed capacity.

The suggested range of face plate strength provided in Section 4 has been applied to some commonly used rockbolts and these results are shown in Table 2. The range has been chosen to fit between the yield load and the tensile load of the bolt, but trying to keep some load capacity margin for the rockbolts to avoid unstable conditions. With seismically active ground, it is suggested to keep the strength range close to the maximum in order to obtain as much retainement capacity as possible and better energy dissipation.

**Table 2 Suggested plate collapse load ranges for some commonly used rockbolts**

| | Static, high stress and quasi-static conditions | | | Light to fair seismicity |
|---|---|---|---|---|
| Bolt | Yield load (kN) | Ultimate load (kN) | Plate collapse load range (kN) | Comments on dynamic conditions |
| Threaded rebar 20 mm Gr60 | 98 | 142 | 89–125 | Use domed/volcano plate close to maximum of range |
| Threaded rebar 22 mm Gr60 | 123 | 185 | 133–169 | Use domed/volcano plate close to maximum of range |
| Forged head rebar 20 mm Gr60 | 129 | 194 | 133–178 | Use domed/volcano plate close to maximum of range |
| Forged head rebar 22 mm Gr60 | 160 | 240 | 169–222 | Use domed/volcano plate close to maximum of range |
| Standard ERB | 110 | 120 | 89–111 | Not recommended |
| Super ERB | 220 | 240 | 214–231 | Use domed/volcano plate close to maximum of range |
| Most dynamic rockbolts | 130–180 | 180–240 | 150–240 | Plate should match specific bolt properties with collapse close to maximum of range |

# 7 Conclusion

The requirements for the compatibility of the face plate with the rockbolt used have been discussed for static, yielding, and dynamic loading conditions. It has been shown that, due to the specific yield and tensile load capacity of different rockbolts, the collapse load of the plate should not exceed the tensile load capacity of the rockbolt unless the loading conditions are completely defined and controlled over time, but the nut/bolt head should not pull through the hole of the plate even at the tensile load of the bolt.

It was also discussed that the ASTM F432 Standard for rating the face plate are not well adapted to follow design guidelines to address the need for tighter load capacity range for face plates. It was suggested to use a range of collapse load values instead.

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