Behaviour of Steel Plates During Rockbursts

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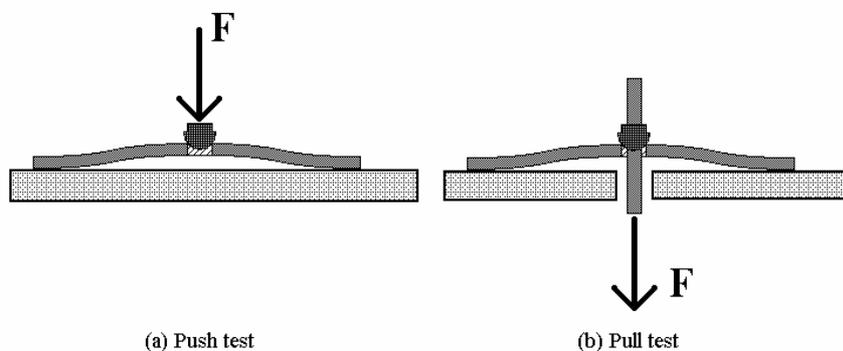**M. Palape** *SRK Consulting Chile S.A., Chile*

Abstract

We present the results of tests on five different types of steel plates subjected to static load under boundary conditions simulating those observed in the field. The test consisted of setting the plates on two supports 8 cm apart and then applying load to the centre of the plate. It was found that the maximum load ranged from 30 to 60 kN depending on the plate design. Such loads are significantly lower than those obtained from tests in which the plate is loaded against a flat surface.

1   Introduction

Steel plates play an important role in retaining systems used for support of underground excavations in rock. It is usually assumed that the steel plates will be able to transmit the full load capacity of the retaining system to the rock bolts or cables. Thus, the capacity of the steel plate should be equal to or greater than the load capacity of the bolts or cables.
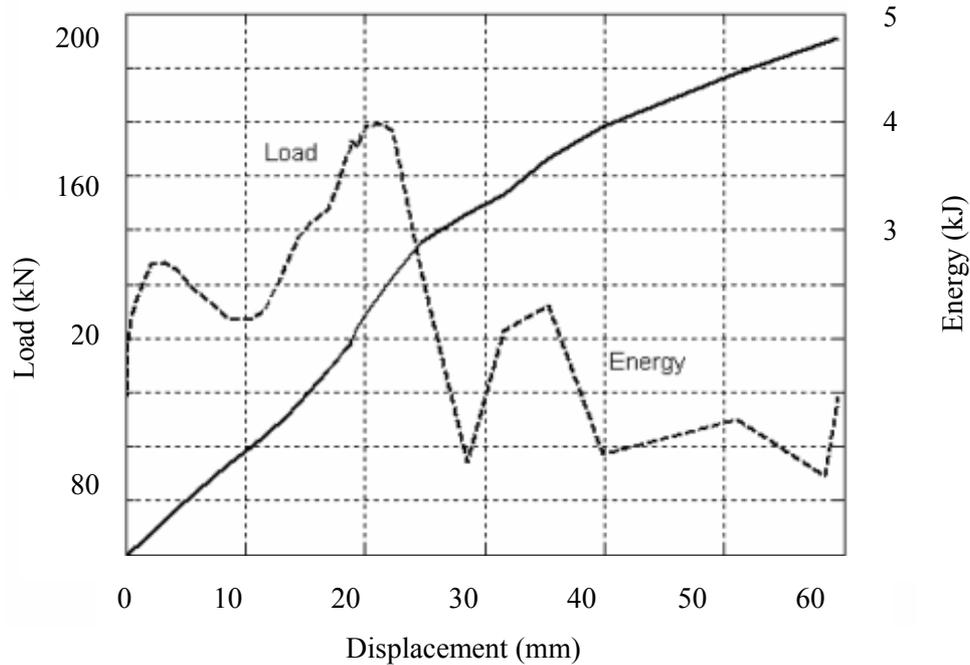
Typically, the steel bearing plates are tested for compression by loading them against a flat surface. The load can be applied by pushing directly over the plate (Figure 1a) or pulling through a bolt and nut connection (Figure 1b). The pull test can be used to evaluate whether or not the nut can pass through the bearing plate central hole or the nut can slide along the bolt.

Figure 1   Different procedures used to test steel plates in the compressive failure mode

Figure 2 illustrates the result of a compression test on a 200 by 200 mm plate made of 4 mm thick steel and tested using the pull test shown in Figure 1b. The results are typical of several plates tested under the same conditions. Full contact of the steel plate against the concrete reaction surface is obtained after approximately 5 mm of displacement. The bolt yields at a load of approximately 110 kN. The maximum load of 160 kN is reached with a total displacement of 20 mm. Additional displacement of the bolt is due to the slip of the nut. Before the nut starts to slip, the plate absorbs a total energy of approximately 2 kJ. Thereafter, an additional 2.5 kJ are dissipated by slippage, so that the total energy dissipated by the system reaches up to approximately 4.5 kJ.

The results suggest that the plates can easily exceed the yield capacity of the bolt. This result can be taken as proof that the weakest link in the support system will be somewhere else. It was also possible to observe that the steel plate can absorb a significant amount of energy, thus contributing to the energy absorbing capacity of the support system.

Figure 2   Results of a pull test on a steel plate reacting against a flat surface

Field observations of failed steel plates after a rockburst show that in many cases the plates fold along a mid plate axis and they often pass over the nut, as it is illustrated in Figure 3.
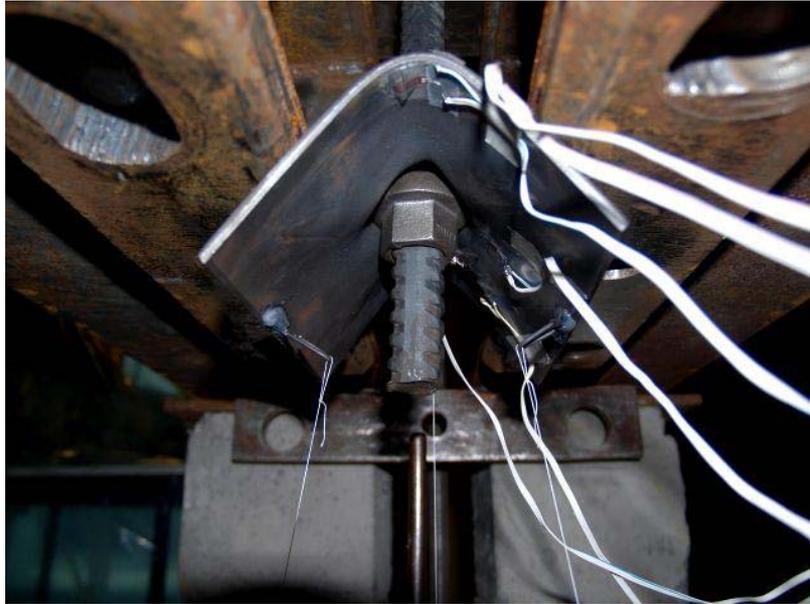

Figure 3   Steel plates which were bent and pushed over the nut during a rockburst

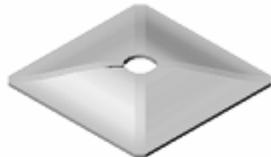These observations led to the development of a test that reproduces the boundary conditions observed in the field.
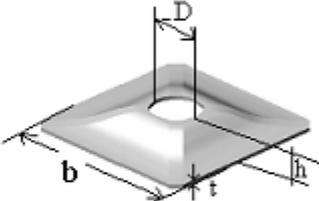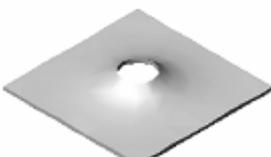
2   Tests

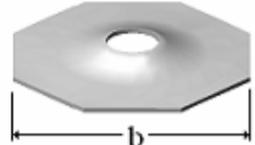Several models of steel plates were tested. The test consisted of setting the plates onto two supports 8 cm apart and then applying load by pulling a bolt with a nut resting on the centre of the plate until the plates folded. The deformation observed during the tests closely resembled the deformation seen in the field, as is illustrated in Figure 4. Details of the test results and interpretation are given by Palape (2007).

Figure 4   Deformation of a plate during the test

Table 1 summarises the properties of the plates tested, Table 2 shows some of the experimental results and Figure 5 illustrates the average test results for all the plates.

Table 1   Dimensions of the plates tested

Type	Width b (mm)	Thickness t (mm)	Heigth h (mm)	Hole diameter D (mm)	Shape
P1	200	5	23	34	
P2	150	5	23	41	
P3	200	4	20	34	
P4	150	4	19	34	
P5	150	4	19	41	

Table 2   Summary of test results

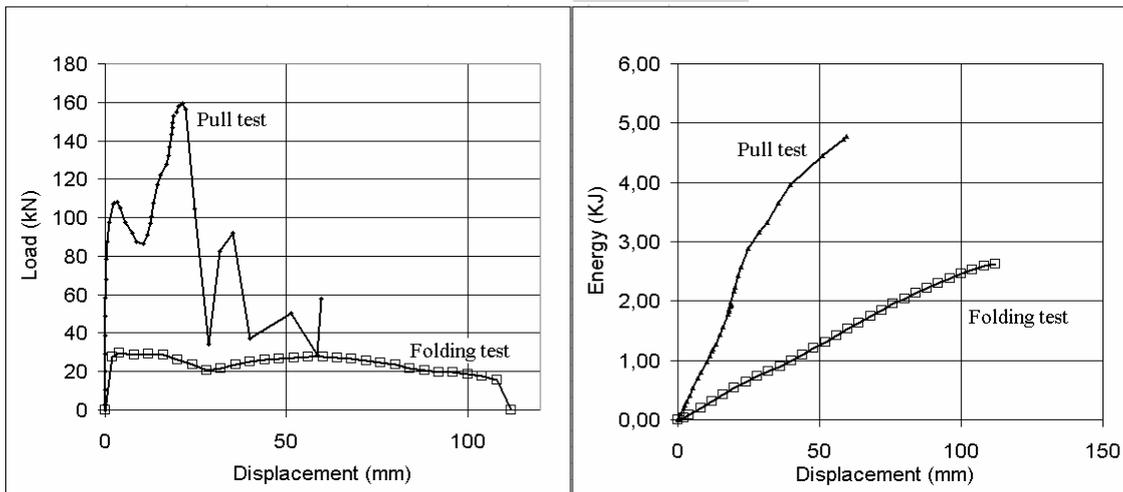| Type	Failure mode	Number of Tests	Peak load (kN)				Average dissipated energy (J)
			Average	Standard deviation	Maximum	Minimum	
P1	Tearing	6	29	7.15	40	20	2612
P2	Nut passes	3	77	7.53	85	71	1646
P3	Bending	3	31	1.64	33	28	1566
P4	Bending	3	32	4.35	36	29	1345
P5	Bending	3	34	3.71	38	32	1309

Figure 5   Summary of folding tests

The maximum average energy dissipated in the tests was obtained for the plates of type P1. However, these plates show the largest dispersion in the tests results, with the dissipated energy of the different tests varying ± 40% from the average.

The maximum load capacity was measured for plates of the type P2. Due to the large diameter of the perforation for the bolt (41 mm) the failure of these plates was the result of the nut passing through the perforation. This is a brittle failure mode then, although the energy dissipated by these plates is similar to that of plates P3 to P5, their maximum displacement capacity is only 40 mm, whereas the other plates reached displacements of 60 to 110 mm.

Since plate types P3, P4 and P5 failed by bending, they developed a large displacement capacity with low dispersion of the test results.

Figure 6 compares the results of the folding test P1 with the compression test shown in Figure 2. It can be seen that there is a significant load and energy capacity reduction when the plates are allowed to bend rather than to be pushed against a flat surface. However, the plot for the compression test included the energy dissipated during the sliding of the nut along the bolt, which took place after 20 mm of displacement. If the energy dissipation excludes the nut sliding, the folding mode of failure of plates P1 would dissipate more energy than when failing against a flat surface.

Figure 6   Comparison of a pull test and a folding test on similar plates

The comparison of the different failure modes can not be based solely on the energy absorption capacity of the plates. Since the support system is made up of several elements interacting dynamically during the response to a rockburst, it is necessary to carry out a numerical analysis that includes all the elements with their respective load displacement behaviour (Van Sint Jan, 1994).

In order to illustrate the relevance of the failure mode, the support system was modelled as several masses connected by springs and dashpots, subjected to the impact of 19.6 kN of rock (0,75 m^3) at a velocity of 6 (m/s). Figure 7 illustrates the model.

Solving the equilibrium of the system shown in Figure 7, the system of equations (1) is obtained

$$[\mathrm{M}]\{\ddot{x}\} + [\mathrm{C}]\{\dot{x}\} + [\mathrm{K}]\{x\} = \{0\}$$ (1)

Where:

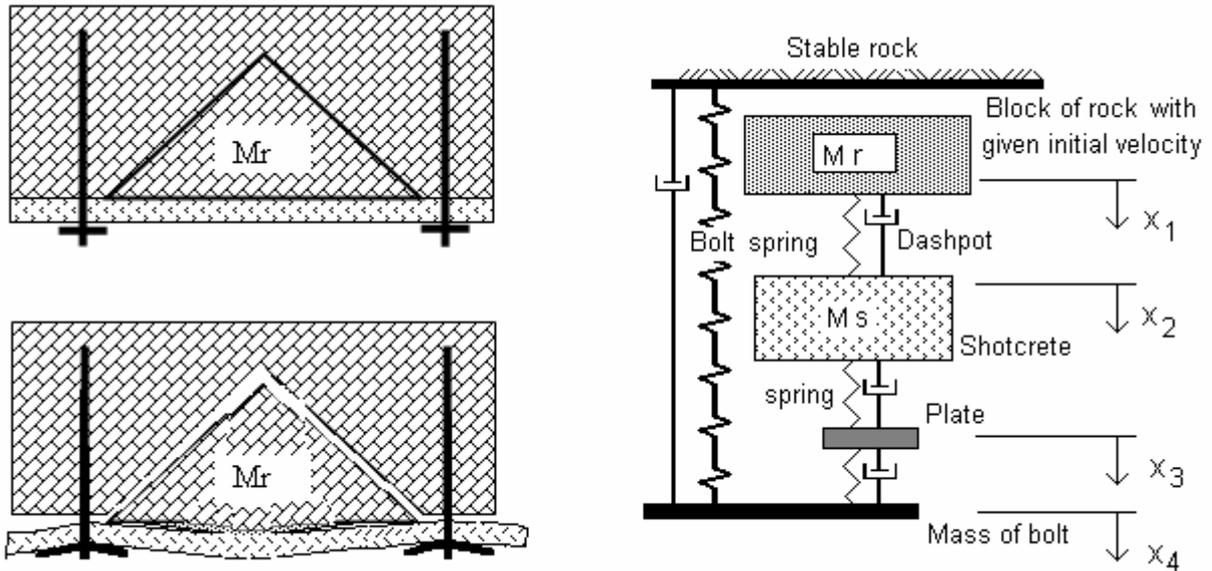|		
|M|	=	mass matrix.
|C|	=	matrix with the damping coefficient of the dashpots.
|K|	=	matrix with the stiffness coefficient of the springs.
{x}	=	vector with the displacements of the different masses.

Dots indicate derivatives with respect to time.

Numerical solutions of the system of equations given by (1) with the appropriate initial conditions, were obtained using Newmark's beta method (1962). The solution was developed for $\beta = 1/6$ (linear variation of the acceleration between integration points) and with small time steps in order to keep the numerical convergence and stability. The damping coefficient was 5% of the critical damping.
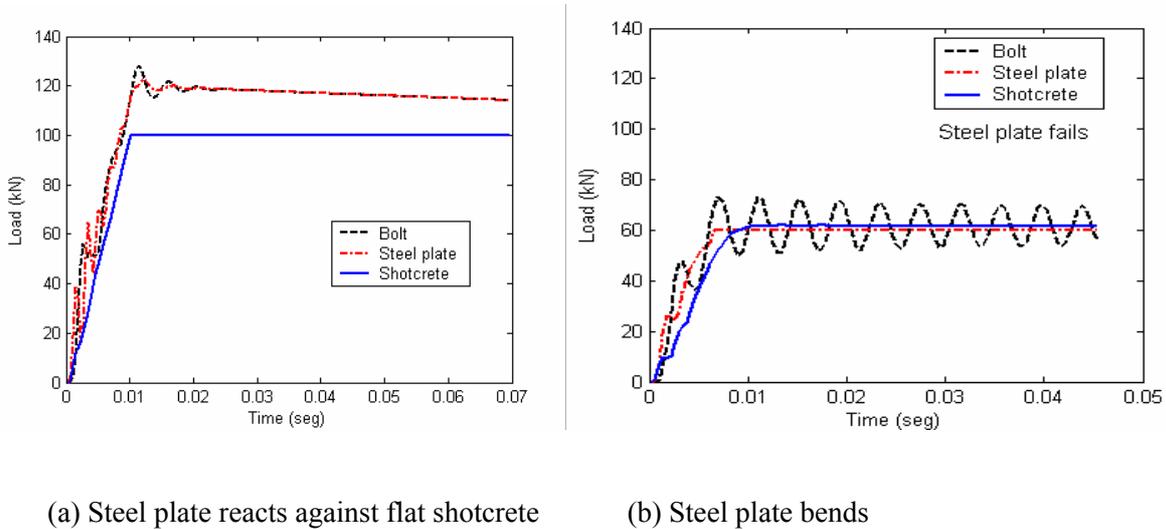
The details of the calculation procedure are given in other publications (Van Sint Jan, 1994; Gaudreau et al., 2004). Two cases were considered, the first one simulates a steel plate failing against a flat surface (Peak load of 100 kN and failure at a displacement of 2 cm); the second case simulates the same steel plate failing by bending (folding mode, peak capacity 30 kN and failure displacement of 10 cm). The shotcrete strength was taken as 60 kN/m^2 and its failure displacement as 15 cm. The two bolts are fully bonded bars with combined strength of 200 kN and failure displacement of 5 cm.

Some results of the analysis are shown in Figure 8. If the plate deforms in the compression mode, the plate and the bolt oscillate back and forward as the load in the shotcrete increases to the yield value; the load in the bolt and the plate decreases after the shotcrete starts to yield and until it fails after 0.03 seconds. If the plate folds, it reaches its maximum load capacity and folds continuously until it is no longer able to hold the shotcrete and the system fails shortly before 0.03 seconds. In the first case, it is concluded that the design should aim at increasing the flexibility and ductility of the bolts and the strength and ductility of the shotcrete

or the mesh. The second case illustrates that the improvement of the bolt and shotcrete performance may be useless if the plate design is not improved accordingly. The analysis is rather simple and the results must be interpreted with caution, but it serves to illustrate the need to perform a dynamic analysis of the whole system.

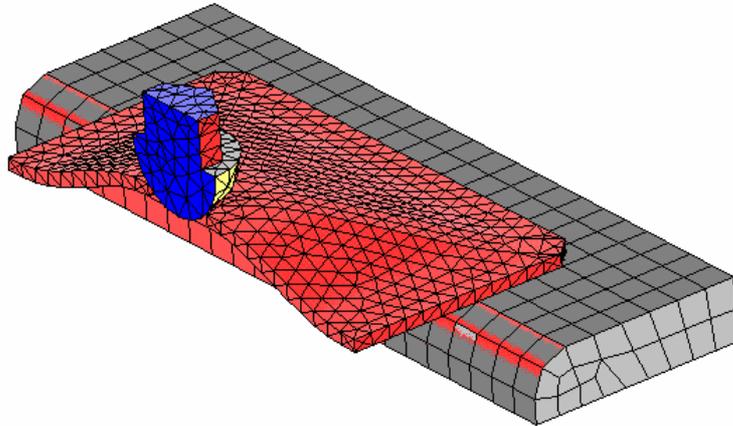**Figure 7   A model to study the dynamic response of the support system**

(a) Steel plate reacts against flat shotcrete   (b) Steel plate bends

Figure 8   Computed response of the support system subjected to a rockburst

It is interesting to note that, in the first case, only the shotcrete reaches it maximum strength and deformation capacity (data not shown in the figure), whereas in the second case it is only the steel plate that develops its full capacity. It is then clear that the total energy dissipated before the failure of the support system is less than the sum of the individual energy capacity of each of its components. The previous result is a consequence of the interaction among the components of the retaining system.

The previous observation leads to the conclusion that it is not possible to evaluate the factor of safety of the support system by simply comparing the sum of the energy capacity of its individual components against the kinetic energy of the ejected block of rock. The adequacy of the support system can be evaluated by performing a numerical analysis that includes the load-displacement behaviour of all its components.
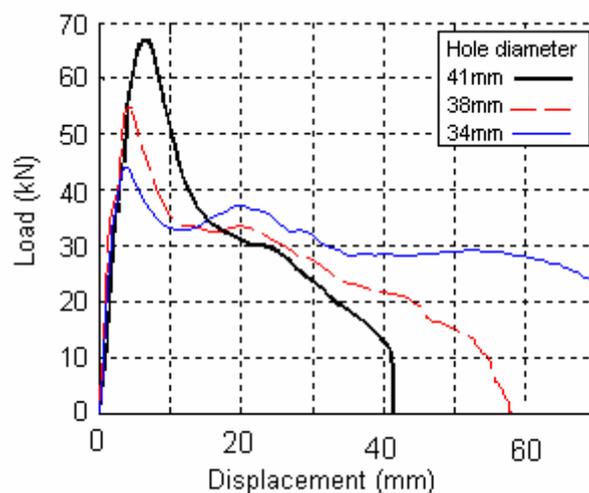
3 Numerical modelling

In order to develop a tool that may be useful for the design of the plates, the test was reproduced using a 3-D Finite Element Code (ANSYS). The model included the nut, the plate and the reaction frame. Because the test set up is symmetric with respect to a vertical plane, only one half of the sample was modelled, as it is shown in Figure 9.

Figure 9   Three dimensional mesh for the numerical analysis

The geometry of the plates was measured with a position sensor mounted on a moving arm. The difference of the computed volume with that measured by immersing the plate in water, was less than 3%. Particular care was necessary in the input of the stress strain curve for the steel; its mechanical properties were measured from small samples taken from the plates. Once the model was thus calibrated, it was used to study the influence of several variables on the behaviour of the plates. For example, Figure 10 shows that as the diameter of plates P2 is reduced, the maximum load also is reduced but the failure mode changes to bending and the maximum displacement increases significantly. The previous result indicates that the total energy dissipated in the test increases.

Figure 10   Computed behaviour of plates P2 for different perforation diameters

4 Conclusions

Field observations show that steel plates subjected to dynamic loading from a rockburst commonly fail in the folding mode.

Laboratory tests of some typical steel plates have shown that their load capacity in the folding mode of failure can be reduced to 20% of the capacity developed with the compressive mode of failure, typical of standard tests.

The maximum displacement of the plate relative to the shotcrete can reach up to 15 cm in the folding mode, as compared to approximately 2 cm in the compressive failure mode.

In order to evaluate the adequacy of a support system to retain a particular rockburst, it is necessary to study the dynamic interaction among all the support elements. The sufficiency of the support can't be accurately predicted by simply adding up the energy absorption capacity of the individual components.

The results of a Finite Element analysis suggest that changing the diameter of the central perforation can significantly improve the dynamic behaviour of a steel plate. The use of such Finite Element code can be used to improve the design of the plates.

References

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