

# Characterising the behaviour of rockbolts based on in situ pull tests

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## Abstract

*The effective use of analytical and numerical ground support design tools requires the use of reliable and representative data on the behaviour of ground support under load. In practice, such data are limited and not readily available. This paper reports on the construction of a comprehensive database of in situ rockbolt pull tests conducted in Ontario underground hard rock mines. This database includes tests on the complete range of rockbolts currently used in Ontario mines. The data were further analysed to develop practical guidelines on the pull capacity and deformation characteristics of the tested bolts.*

**Keywords:** rockbolts, in situ pull tests, underground mines

## 1 Introduction

The majority of underground hard rock mines undertake in situ pull testing of rockbolts for a variety of QA/QC purposes. This usually involves testing a number of bolts on an annual basis, or a percentage of all bolts installed. In situ pull tests are also undertaken as part of the introduction of a new or modified reinforcement element at a mine site. Under these circumstances, the objective is to demonstrate that a particular rockbolt can first be installed and, subsequently, that it can provide the required performance in a set of specific ground conditions.

An equally important benefit of an in situ testing program is to determine the necessary input parameters for the design of rock reinforcement. Depending on the employed design tools, it is important to determine the working capacity as well as the stiffness of bolts. This implies that it is necessary to characterise the behaviour of rockbolts under axial loads.

This paper reports on the construction of a comprehensive database of in situ rockbolt pull tests conducted in Ontario underground hard rock mines. This database included tests on the complete range of rockbolts currently used in Ontario mines. The data were further analysed to develop practical guidelines on the pull capacity and deformation characteristics of the tested bolts.

## 2 Laboratory versus in situ pull tests

In situ pull tests are the standard method used for assessing the performance of rockbolts under axial loading under field conditions. Laboratory tests have the advantage that the tests are performed under controlled testing conditions and that the results should be relatively repeatable. Nevertheless, there are limited published, and easily accessible, results of laboratory pull tests of rock reinforcements. The most quoted approach involves embedding one or more bolts through two high-strength concrete blocks which can then be loaded axially in tension (Stillborg 1993; Stjern 1995). Li et al. (2014) reproduced the results of Stjern (1995) and provided some more recent tests on energy-absorbing bolts. Although laboratory tests provide greater control over testing conditions and in theory results should be relatively repeatable, using concrete blocks may not necessarily represent field rock mass conditions. Furthermore, installation procedures in the laboratory can be quite different from in situ practice.

In this context, in situ pull tests are of interest as they are relatively inexpensive, employ simple apparatus and procedure, and are better indicators of actual performance. The main limitation of in situ pull tests is that the tests are seldom brought to failure. Another limitation, that can be easily rectified going forward, is that for the majority of in situ pull tests, the load–displacement relationship is not always recorded. In a detailed review of rockbolt in situ tests undertaken in Ontario hard rock mines, it was noted that although there are both ASTM International (2013) and International Society for Rock Mechanics and Rock Engineering (1981) suggested methods, these are not consistently followed. In effect, when a load–displacement curve is recorded, the test is often stopped at the yield point of the bolt. Consequently, in the majority of in situ pull tests, it is not possible to determine the ultimate capacity. A useful reference point in the interpretation of these test results is to associate the onset of yield with the working capacity of the rockbolt under static loading conditions. The concept of working versus ultimate capacity is illustrated in Figure 1.

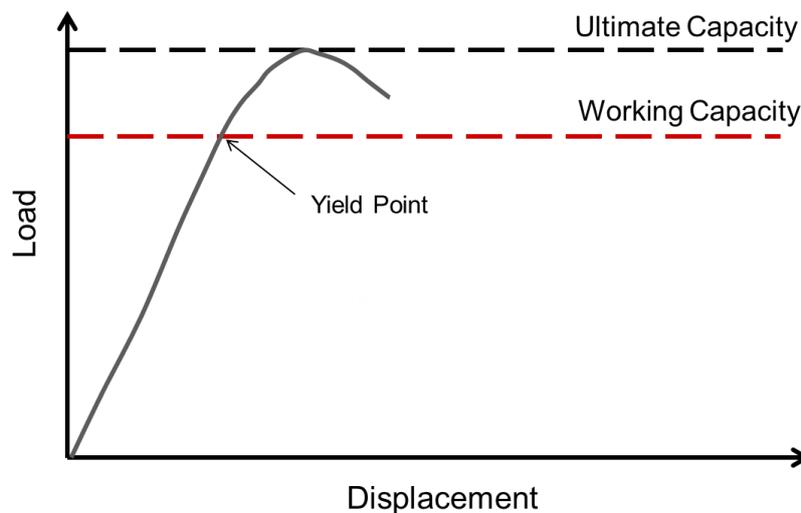


Figure 1 Conceptual representation of working and ultimate capacity of rockbolts

The rockbolt ultimate or working capacity is a necessary input parameter in analytical and limit equilibrium analysis of the impact of rock reinforcement on the stability of excavations in rock subjected to static conditions. An important element of pull tests is the ability to determine the stiffness of the bolts. This, however, is only possible if the complete load–displacement curve is recorded during the tests. The stiffness of a bolt dictates its performance under different ground conditions. The secant stiffness is the average stiffness of the bolt response from initial loading to working capacity. It captures all sources of deformation/displacement as well as any progressive softening of the bolt response. Rockbolt stiffness is critical in defining the behaviour of reinforcement, and a prerequisite in all numerical models that explicitly model reinforcement.

### 3 The in situ rockbolt pull test database

A comprehensive database of in situ pull tests was constructed from 18 underground hard rock mines and in collaboration with Workplace Safety North. The collected pull test reports were prepared by internal mine personnel, third party contractors, or representatives of ground support suppliers. It should be noted that the majority of pull tests performed after 2010 appear to have been outsourced to ground support suppliers.

Once the database was constructed, it was further reviewed to reject pull test results that were incomplete or defective. A further subset of the database included tests that reported the complete deformation curves. This has allowed the determination of rockbolt stiffness as well as working capacity. An indication of the relative stiffness of the rockbolts is important in understanding the in situ behaviour of the bolts.

## 4 Rockbolt performance data

This paper presents selected results from the analysis of the in situ pull tests. This is valuable information in that the general behaviour of rockbolts is assumed to be captured by the composite graph based on very limited laboratory tests (Stillborg 1993). Although this appears to be conceptually correct, the reality is that the test configuration (concrete blocks representing the rock mass) clearly has a direct impact on the bolt behaviour. Stillborg (1993) performed pull tests on a variety of bolts by installing three bolts across a simulated joint in high-strength concrete. These tests included mechanically anchored bolts, resin and cement grouted rebar bolts, friction rock stabilisers (FRS), and expandable bolts. Pull tests performed by Stjern (1995) simulated joint loading and tested a greater variety of bolts than Stillborg (1993).

Conceptually, for continuously mechanical or frictional coupled bolts, these tests, which simulate joint loading, would produce a stiffer result than the approach used for in situ testing. While this loading method replicates the commonly expected loading pattern of the installed bolt (reinforcing the rock mass across a discontinuity), the difference in bolt loading prevents a direct comparison of these laboratory results to in situ data.

A further natural limitation of the work of Stillborg (1993) and Stjern (1995) is that it does not provide information on the several types of rockbolts introduced since 1993. This has led to several suppliers in superimposing a 'characteristic' load–deformation curve of new reinforcement elements on the Stillborg (1993) data. Given, however, that these new data were mostly obtained under different test conditions, for example pipe tests, this is not a representative comparison. Tests in pipe tubes result in different confinement and apparatus stiffness than tests in concrete blocks.

### 4.1 Load–displacement plots of rockbolts from in situ pull tests

Following a review of the Ontario Rock Bolt Pull Test Database, a series of statistical tests were used to characterise the performance of the various bolts. This has allowed the investigation of the compliance of bolts with supplier specifications, working capacity, etc. Of particular interest was to provide representative load–deformation plots for rockbolts using the in situ pull test database. The first step in this process was interrogating the database for all tests that reported both the load and deformation, as well as the working capacity of the bolts. The mechanism of the bolt was also taken into consideration and, where appropriate, the results were analysed per bolt length.

#### 4.1.1 Methodology

The methodology to construct the load–displacement plots followed the approach by Nicholson and Hadjigeorgiou (2018). This employed approach is illustrated with reference to the analysis for FRS. Figure 2 illustrates the load–displacement data for FRS in the database between 1.7 and 2 m long. The percentiles of displacement at specific ½ tonne intervals of load were calculated, and the variation in capacity and displacement profiles was used to construct displacement load distributions. The resulting 10th, 25th, 75th and 90th percentiles of displacement developed are depicted in Figure 3.

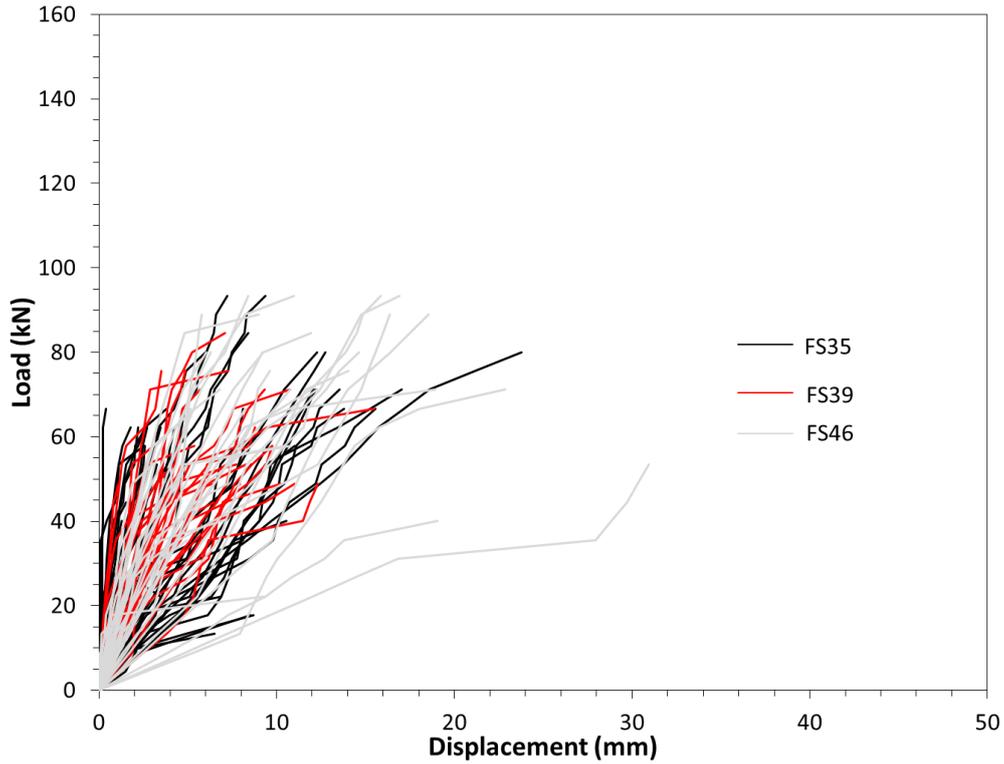


Figure 2 Load–displacement curves of FRS in the database

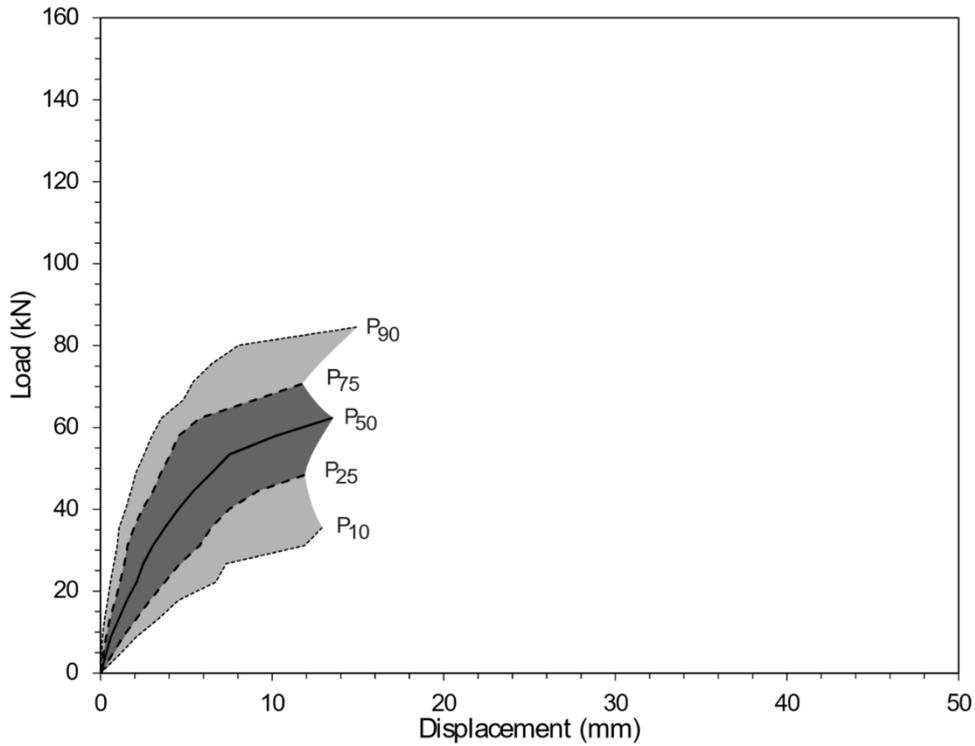


Figure 3 Load–displacement distributions for FRS

In Figure 4, these percentiles were combined with the distribution of displacement, normalised to the anchorage length of the bolts. In this case, capacity is in kN/m, and displacement is a percentage of anchorage length.

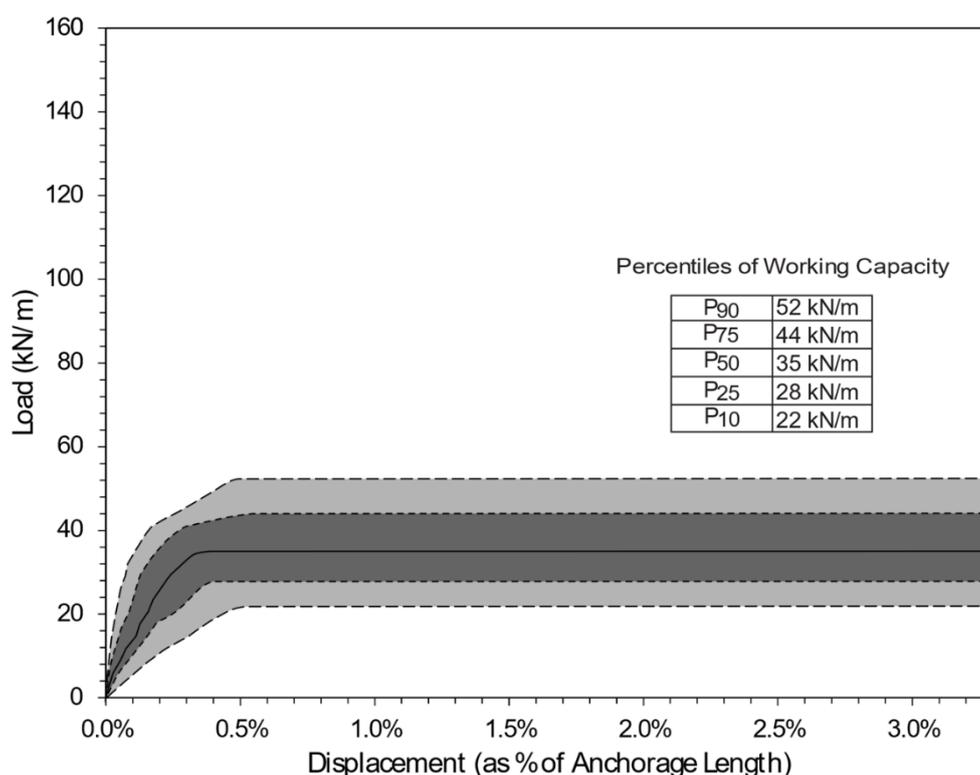


Figure 4 Composite distribution of FRS response

There are several benefits in displaying the results in this format, as they can be used for probabilistic design and allow the user to make an informed decision on necessary input parameters based on tolerance to risk, significance of excavation, and other factors.

#### 4.1.2 Representation of load–deformation

The same methodology was used to describe the performance of a range of rockbolts used in underground hard rock mines. It should be noted that resin was used as the grouting agent for rebar, D-Bolt and modified cone bolts. The load–displacement plots in Figure 5 were constructed using the median working capacity of these bolts. For comparative purposes, the FRS capacity was plotted for 1.8 and 2.4 m long bolts. This is significant in that it reiterates the observation made in this investigation and in previous work by Nicholson and Hadjigeorgiou (2018) and Tomory et al. (1998) that the controlling factor in FRS bolt capacity is bolt length. In fact, there is no statistical evidence that FRS bolts of larger diameter provide a higher pull test axial capacity.

Figure 5 shows that the working capacities of 22 mm rebar, ‘super’ expandable bolts, and 22 mm D-Bolts are similar. The high capacity is a critical factor in using these bolts in ground conditions where a high static demand is anticipated. The lowest working capacity is the FRS, though the median plough point of modified cone bolts (MCB) is somewhat lower and this value could be reasonably treated as the MCB working capacity. The complex behaviour of MCB has been discussed in greater detail elsewhere (Simser et al. 2007). Both diameters of rebar bolts, as well the 20 mm D-Bolt, provide for a stiff reinforcement. The MCB has the lowest secant stiffness, though the pre-plough bolt stiffness of MCBs is similar to a 1.8 m (6’) mechanically anchored bolt or FRS. ‘Standard’ expandable bolts are the most ductile of included bolt types.

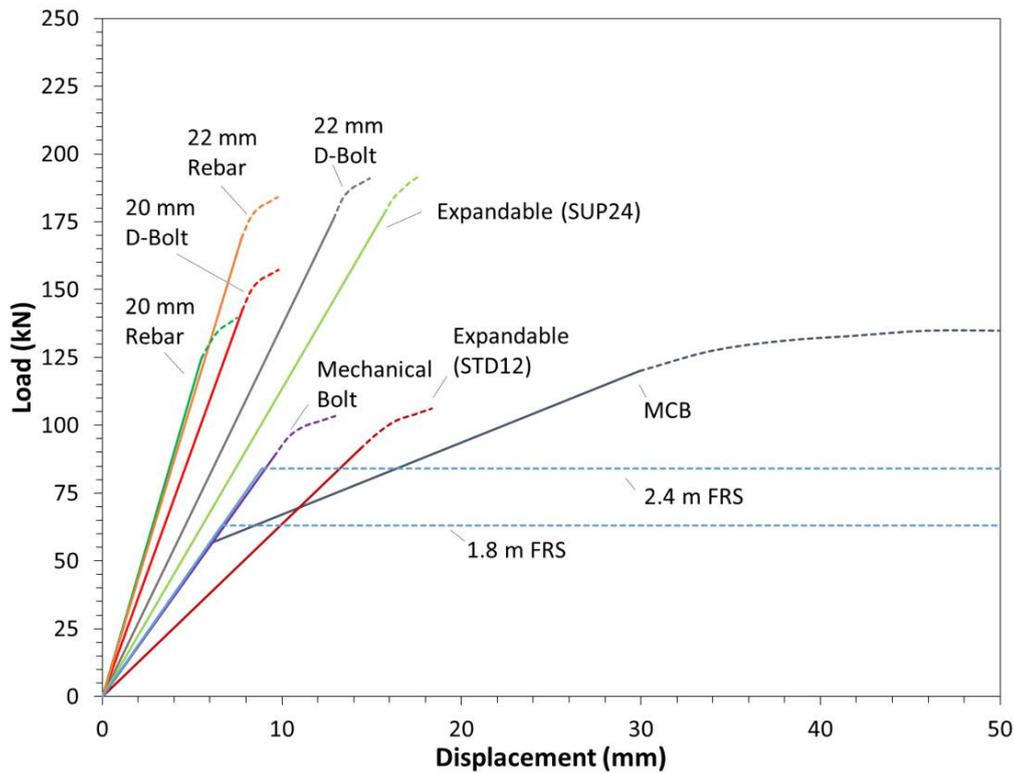


Figure 5 Load–displacement plots of rockbolts from in situ pull tests

A direct comparison between the results from the in situ pull tests and the composite laboratory tests by Stillborg (1993) and Stjern (1995) is difficult given the difference in the bolts used. A cursory comparison is shown in Table 1, where n is the number of tests per rockbolt type.

Table 1 Summary of results for similar bolts tested by Stillborg (1993) and Stjern (1995)

Source		20 mm resin grouted rebar		Mech bolt		'Standard' expandable bolt		Friction stabiliser	
		kN	n	kN	n	kN	n	kN/m	n
Field	Working capacity	127	96	84	49	98	26	36	603
Stillborg (1993)	Working capacity	154	3	84	3	75	3	32	3
	Ultimate	181		88		113		32	
Stjern (1995)	Working capacity	140	2	n/a	n/a	106	1	47	2
	Ultimate	156		n/a		108		50	

Both Stjern (1995) and Stillborg (1993) bolts were tested across a simulated joint in two concrete blocks and, as such, the working capacity (yield) of the rebar is higher than the database results (150 versus 125 kN), given that for in situ tests, load is applied to the lower-diameter threading. The laboratory results are also stiffer. This can be attributed to the loading method, with a simulated joint lacking the non-encapsulated portion protruding from the borehole. For FRS bolts, Stillborg (1993) tested an FRS with a nominal diameter of 39 mm, whereas Stjern (1995) tested 46 mm FRSs. Stillborg found little to no displacement of the FRS before the onset of slip, whereas field data and Stjern found both pre-slip displacement and an initial slip that is lower than the maximum resistance. However, Stjern found a

length-adjusted resistance of FRSs (53 kN/m), which is much higher than field data (35 kN/m), Stillborg (32 kN/m) or Tomory et al. (1998) (32 kN/m). Although the expandable bolt configurations tested by Stillborg (1993) and Stjern (1995) are no longer in use, they can be generally compared to the 'standard' expandable bolts in the database. The bolts tested by Stillborg exhibited a very stiff response before slipping at 108 kN, whereas both Stjern and the field data showed yield/failure in the bolt itself. The Stjern tests were significantly stiffer than field data as well. Mechanical bolts were tested by both Stillborg (1993) and Stjern (1995), with Stjern testing multiple diameters and galvanised varieties. When comparing similar diameters to the database, similar working capacity values were found.

It is important to recognise the specifics and limitations of the results from the laboratory tests, as quite often, it is these values that are used in stability analysis and ground support design. This has significant implications given the variation in performance between laboratory and in situ test pull-out tests.

It should again be reiterated that the presented design charts are based on empirical data from in situ axial pull tests. The actual loading mechanism in an underground environment may in fact be more complex.

## 5 Impact for design

The projected distributions for ultimate capacity can be useful in the design of ground support standards for static loading conditions. The first step is the selection of an appropriate, or acceptable, percentile of performance for the displacement response and capacity. This value will be a function of the stage of the project (feasibility, design, operation, etc.) and the quality and quantity of all pertinent geomechanical data. For example, in the early stages of design, the 10th percentile of stiffness and ultimate or working capacity, depending on bolt type, may be selected. This means that 10% of the bolts in the database displayed displacements greater than the depicted  $P_{10}$  at a given load in Figure 4, and 10% of the bolts in the database had ultimate capacities lower than 22 kN/m.

The significance of the rockbolt stiffness on the results of any stability analysis cannot be understated. For example, Bobet (2006), using analytical solutions, demonstrated that the most important factor that controls the load of a bolt in elastic ground is its relative stiffness with respect to that of the ground. It follows that in numerical models that use explicit techniques to represent rock reinforcement, the use of laboratory-based rockbolt stiffness may provide misleading results.

## 6 Conclusion

This paper reports on the database of a range of rockbolt pull tests in Ontario mines. It reviews the load–displacement behaviour of bolts subjected to pull tests to provide a series of performance metrics. The influence of bolt, installation and rock mass on pull test results has been investigated.

Finally, a composite plot is presented based on the working capacity of several bolt types, as determined from in situ tests. This design chart has the advantage of capturing the relative stiffness of different bolt types based on in situ as opposed to laboratory tests in concrete blocks. The results of the statistical analysis can provide a reference to rockbolt behaviour and as input to further analysis. The developed charts, on percentile displacement and capacity, can be used as input data to probabilistic rock reinforcement design.

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