

Safety in Mines Research Advisory Committee

Final Project Report

Testing of Tunnel Support: Dynamic Load Testing of Rockbolt Elements to Provide Data for Safer Support Design

WD Ortlepp and TR Stacey

Research Agency : Steffen, Robertson and Kirsten
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Executive Summary

In 1993 a series of tests on rebar rockbolts and cone bolts was completed using impulsive loading, and dynamic testing of wire mesh, lacing and shotcrete was carried out under project GAP 221 which was reported early in 1997. As an extension of this work it was the main purpose of the present research project (GAP 423) to subject several commonly used tendon types to dynamic tensile loading at strain rates comparable with those that are believed to occur during rockbursts. The following tendons, representative of the most commonly used types of rock reinforcement, were tested:

- 16mm diameter rebar shepherds' crooks
- 16mm diameter smooth bar shepherds' crooks
- de-stranded hoist-rope 'slings' ex Vaal Reefs
- 18mm diameter compact strand cable
- 39mm diameter splitset bolts
- standard diameter Swellex rockbolts

The tendons were grouted into steel tubes, or installed in boreholes formed in simulated rock in steel tubes, the dimensions of the tubes being such that they gave confinement equivalent to that provided by the rock mass. The dynamic loading was imposed using a drop weight system impacting on a swing beam.

In initial tests breaking of rebar tendons could not be achieved. It was found that the "softness" of the testing system was allowing progressive debonding of the grouted tendon to occur. This provided a much longer length of tendon along which elongation, and consequent energy absorption, could occur. It later became evident that this phenomenon was to be found in most of the other tendon types as well. It was found necessary to stiffen up the testing system considerably.

The design values derived from the testing are summarised in the Table below.

Test Series	Tendon Type	Rupture Energy kJ	Elongation Energy kJ/100mm	Sliding Energy kJ/100mm
1	Rebar 16mm	4,8 ± 0,7	-	-
2	Smooth bar 16mm	-	13,9	3,0 x l _{ej} - 0.15*
3	Vaal Reefs hoist rope strand	< 2,4	-	0,8 to 8,2
4	18mm compact strand cable	17,5 ± 2,0	-	-
5	39mm diameter splitsets	11,6 to 15	11,6 ± 1,3	3,0 to 6,3
6	Standard Swellex	4,6 ± 0,5	9,9	3,0 to 5,8

* l_{ej} is initial embedded length in metres

Several interesting and important insights into the likely behaviour of support elements under real dynamic operating conditions were revealed by the practical difficulties experienced in the actual carrying out of the test programme. The more important of the insights gained were:

- the very abrupt, even brittle, fracture of fully grouted, fully bonded steel bars which is often observed in a rockburst-damaged tunnel, was not easy to achieve under simulated conditions, probably owing to 'softness' in the loading system. The maximum testing system stiffness attained was probably still well below that of an intact rock mass;
- the practical implication of this phenomenon is that the theoretical deficiencies in energy absorption capabilities of stiff non-yielding tendons are not as evident as they might otherwise be in highly-deforming excavations in hard rock;
- In practice reduced system stiffness will result from such factors as:
 - the prior existence of significant fracturing in the tunnel walls;
 - commencement of de-bonding by some earlier, possibly sub-critical, impulsive load;
 - any 'softer' elements in the support system such as non-stiff face plates, slack lacing, poor quality grout, incomplete grouting, etc;

- where very strong jointed rock (for example, in certain dykes) resists the development of a significantly softer shell of fractured rock around the tunnel, the stiff tendons will be more vulnerable to acute stress concentrations across the joint boundaries of large intact blocks and abrupt failure will be common;
- in uniform straight holes, hollow friction-dependent tendons such as splitsets (and to a lesser extent, Swellex bolts) will not break, but will slide even if the hole diameter is tight; and in the case of splitsets, the hole is not filled with grout.
- the full potential tensile strength of friction-type tendons can only be utilised if the hole is just sufficiently distorted or dislocated to clamp the tendon without shearing it. However, in practice, guillotining and tearing of the steel tube is likely and conventional laboratory-determined strength testing is then irrelevant.
- often it is inadequacies of the terminating arrangements on the tendons such as the welded ring on splitsets, the sealing weld and soft ferrule on Swellex, and the inadequate swaged sleeves on the loops of discard winding-rope strand, that fail prematurely and allow only partial utilisation of the potential strength or resistance of the tendon. These are shortcomings that require urgent attention by the manufacturers.

Probably the most striking and certainly the most significant effect that was consistently observed during the successful tests was the paradoxical tendency of tendons, subjected to a first impulse that was insufficient to break the tendon, to acquire extra capacity for absorbing more energy later if subjected to several impulses. This extra energy was often considerably more in total than was necessary to cause failure at the first impulse. These additional amounts of consumed energy cannot be recognised or utilised in the strict application of the formal design procedure because the situation that permits the phenomenon is really one of conditional stability that cannot be predicted. The un-enhanced rupture energy value is the only quantity that can be used as a design value in a rational design procedure. Naturally, it will lead to a somewhat conservative design, but not one which is unrealistic in any way.

It is concluded from the research project that the creation of a realistic and controllable method of testing support tendons dynamically, which has been achieved, offers a new and fresh opportunity for improving the design methodology for the support of excavations under rockburst conditions and, importantly, also provides an inducement for the development of innovative improvements in the support elements themselves and in their application.

As a result of this research project, a major step forward has been accomplished in that it is now possible to use the same classical rational procedure for the design of tunnel support as is employed for the design of structures or machine components in more rigorous and precise engineering disciplines. Although the design values, which have been summarised in the Table above, are very approximate and have still to be validated against properly documented experience, they do provide a set of data where no data existed previously. Furthermore, the data were derived from simulated actual conditions not from an idealised, laboratory situation.

It is considered very desirable to expand the knowledge in the field of dynamic phenomena in mine tunnels, in the following areas:

- examine the effect of partial dislocation of the drill hole, particularly on the performance of the thin-walled steel tubes of the friction-based tendons, which results from limited shearing on joints or offsets on fractures in the surrounding rock mass;
- check the performance of cone bolts and any other rock bolt types that purport to have a yielding capability, for example square twist bar;
- check on the desirability of prestressing cable anchors to relatively high values of pre-load;
- find further confirmatory data for the beneficial or protective effects of the progressive debonding phenomenon.

With regard to the manufacturers of support items, the following challenges must be met in both the area of existing responsibility and in future innovations:

- the elimination of weaknesses at the collar ends of splitset and Swellex bolts, and de-stranded hoist-rope tendons;
- the development of a simple, partial-locking end arrangement for smooth bars that will ensure their enhanced elongation response even when the effective embedment length is considerably less than the normal critical bond length.

1 Background

In 1993 a series of tests on rebar rockbolts and cone bolts was completed using impulsive loading to evaluate the performance of these retainment support elements under simulated rockburst loading. In these tests the impulsive loading was applied with the use of explosives.

The test results demonstrated graphically the ineffectiveness of conventional rebar support elements in withstanding rockburst loading, and the success that the yielding cone bolts showed in containing the 'rockbursts' with no damage to the elements. The tests were specifically on the retaining portion of the support systems. For a support system to be fully effective in rockburst situations, and to maximise the safety under such conditions, the support system must also be able to contain rock material which is usually ejected with force in rockburst events. It was therefore necessary to test containment support systems under dynamic loading to the level experienced during rockbursts. Such testing was proposed as the project GAP 221 which was completed at the end of 1996 and reported early in 1997.

A fairly comprehensive range of cladding types was investigated and a range of design values was obtained which would enable the suitability of various forms of cladding subjected to dynamic loading to be compared.

It then became apparent that similar quantitative design values for the various types of available retainment support elements did not exist.

2 Introduction

In order to provide quantitative design values for tendons appropriate for use in the design of the support of tunnels under rockburst conditions, Project GAP 423 was commenced early in 1997.

The expected primary output was that -

- Capabilities of alternative rockbolt elements in realistic surroundings under dynamic conditions would be determined.
- Design values for use in design of rockburst support would be obtained.

The potential impact of the research work was expected to be -

- improved safety in mines subject to rockbursts;
- provision of valuable information for the development of improved support systems;

- information to the mines on the performance of commonly used rockbolts under rockburst conditions.

A copy of the research proposal is included in Appendix D for record purposes.

Most rock-support tendons are sold with the assurance that they comply with SABS specifications or with some other quality compliance requirement. Invariably, this only ensures that the materials from which the various components of the device are manufactured conform with expectation, under laboratory conditions. The behaviour of a support element which is in contact with the rock or surrounded by an annulus of grout in a transversely undeformable hole in solid rock and which is subjected to a suddenly applied tensile force somewhere along its length, is unknown and cannot be tested in a conventional laboratory situation.

It was the main purpose of this programme of testing to subject several commonly used tendon types, surrounded by rock or by cement grout, to impulsive tensile loading at strain rates comparable with those that are believed to occur during rockbursts. To introduce shear dislocations in the hole, or shearing components in the loading, was not considered to be appropriate at this stage of rock bolt testing.

The following tendons, representative of the most commonly used types of rock reinforcement, were selected to be tested:

- 16mm diameter rebar shepherds' crooks (fully-bonded, rigid)
- 16mm diameter smooth bar shepherds' crooks (partially-bonded, semi yielding)
- de-stranded hoist-rope 'slings' ex Vaal Reefs (lubricated, helix)
- 18mm diameter compact strand cable (very stiff, pre-stressed)
- 39mm diameter splitset bolts (percussively-driven, friction type)
- standard diameter Swellex rockbolts (inflated friction dowel)

Different lengths of these devices were to be tested, particularly in cases where it was believed that their load resistance would be very sensitive to the embedded length.

3 Testing procedure

The underlying rationale, on which the testing method was founded, was based on the observation that rockburst damage which exposed the limitations of conventional types of support, frequently involved the rapid ejection of a limited thickness of rock from the excavation sidewall or roof. The support tendons would typically fracture at or very close to the separation surface.

The fact that the 'tributary' dead-weight load of the ejected or fallen rock was often considerably less than the strength of the rock-bolts that were broken, proved that the kinetic energy of the limited mass of rock was significantly greater than gravity acceleration could provide. Figure 1 is a typical illustration of such a case. Ejection velocities of 3 to 10 m/s or more are believed to be possible. Often the rock that was ejected and broken up would be as little as one-half metre thick.

3.1 Specimen dimension

It was decided that the 'ejectable' portion of the test piece would be 600 mm long and its 'embedded' length would range from a minimum of 600 mm for 'rigid' rock bolt types whose *critical bond length* was said to be shorter than that, to as much as 2400 mm where resistance to sliding was the 'modus operandi' of the frictional rock stabilizers. In tests where the tendons were fully grouted, the simulated drill hole was created in each case from two lengths of 63 mm outside diameter by 40 mm inside diameter thick walled steel tubing butted together.

Figure 2 shows 3 test pieces into which Vaal Reefs hoist rope strands of 0,6 m, 0,8 m and 1,2 m embedment lengths were grouted. The temporary spot welds which hold the butted ends together are barely discernable 0,6 m back from the near ends of the steel tubes.

Simple elastic deformation calculations showed that the transverse stiffness of the 11,5 mm thick steel annulus was similar to that of a 40 mm diameter circular hole in a semi-infinite quartzite rock mass.

In tests where friction-based 'dowel-action' tendons such as splitsets and Swellex were to be tested or cable anchors were to be grouted into a larger diameter hole of about 65 mm, a longitudinally split tube of 93 mm outside diameter x 64 mm inside diameter was used.

3.2 Grout strength and bond strength

Recognizing the likely important influence on the test results of the shear strength of the

grout/steel interface, it was decided that a standardized grout mix should be used throughout. The Capram system of injected cement paste was adopted for all tests other than the splitsets and Swellex.

The shear strength of Capram grout was determined by CSIR using a simple apparatus that subjected discs of 66mm diameter about 10mm thick to double shear. Eight specimens yield shear strength values that ranged from 6,7MPa to 10,7MPa with a mean value of $9,1 \pm 1,27$ MPa.

The shear strength of the interface between this grout and a steel surface, ie the bond strength, was determined by measuring the force necessary to initiate sliding of a 100mm long plug of grout set inside a steel pipe of 65mm I.D. Four tests yielded values of 640,740, 1120 and 1130 KPa.

3.3 The simulated drillhole

A considerable effort was devoted to an attempt to achieve a good simulation of the frictional properties of a percussively-drilled hole in a typical hard rock.

A very strong, very fine-grained "concrete" made from a 1:2 mix of high alumina cement and screened $\leq 1,0$ mm hammer-milled andesite aggregate was carefully pressed around a 25mm diameter steel rod to form a semi-annulus in each half of the 93mm split tube. After the concrete had cured the steel rod was removed and the two half shells were bonded and clamped together. An indication of the effectiveness of the bonding and the method of clamping can be gained from Figure 3. The 25mm pilot hole was then reamed out to a final diameter of 36,5mm in several stages by tungsten carbide tipped masonry drills driven by a rotary/percussive electrical drilling machine which was mounted on a rail-guided carriage to ensure co-axial straightness. The finished hole was straight, looked relatively smooth, but felt fairly "sharp" to the touch.

Inflating the Swellex tubes into the simulated drill-hole presented no problems, but the installation of the splitsets proved to be extremely difficult.

3.4 The impulse-loading system

The larger diameter split-shell specimen holder was clamped together at intervals of 250mm by pairs of thick-walled, accurately machined 'half-shell' clamps 100mm long bolted together

by means of four 25mm MF high tensile bolts, see Figure 4.

One similarly sturdy, but longer, clamp 150mm long with 6 bolts was carefully machined to seat precisely into a 3mm deep landing at the lower end of the 'ejectable' portion of the simulated hole. This provides the 'anvil-collar' through which the tensile impulse load was applied to the test piece. Figure 5 shows the anvil collar around the 63mm outside diameter test piece in position below the 'jaw' of the swing beam end and Figure 2 shows the 3mm deep landing into which the anvil-collar clamp is seated.

Another identical 6-bolt clamp seated in a landing machined 3mm deep into the upper 'embedment' part of the specimen holder allowed the test assembly to be suspended from the steel superstructure of the dynamic testing apparatus.

The impulse is applied to the anvil collar of the specimen holder by the 'knuckled-end' of a very stiff 820kg mass swing-beam of 1,0m effective length - see Figure 5.

The west end of the swing beam is pivoted at the 'eye' of a 90mm diameter solid steel suspension bar which is visible just right of centre in Figure 6. This photograph also shows the general arrangement of the dynamic test facility and the two drop weights on the right.

The conceptual design of the test method is shown in Figure 7.

An exactly determined energy pulse at known impact velocity can be imparted to the midpoint of the swing beam simply by controlling the drop height of the impacting mass. Because the inertial mass of the swing beam (820kg) is considerably less than that of the striking mass which was usually 1048kg, and occasionally 2706kg, the transfer of momentum function ensures that the initial velocity of the beam midpoint is much greater than the velocity of the drop weight at impact. This midpoint start velocity is doubled at the point of application of the load to the test-piece, by the simple geometry of the swing beam arrangement.

The very high values of the theoretical start velocity would be achieved if the swing beam was supported only by a link or thread of marginally sufficient strength which would break easily and instantly at the moment of impact. When restrained by the substantial initial resistance

of a test specimen, the actual start velocity is theoretically indeterminate and would range from quite low values to fairly high values. A novel gravity-driven cylindrical chart recorder was developed in order to attempt to trace the actual velocity of strain imparted to the test piece.

The quality of the data that could be obtained from the velocity recorder is shown in Figure 8 which depicts the velocity changes that occurred during the two impulses imparted to the de-stranded rope sling of test No. 22 (Series 3). The first impulse of 1,37 kJ produced a theoretical start velocity (at the end of the swing beam) of 27 m/s which caused an initial 'strain velocity' or, more correctly in this case, a 'sliding rate' of 7,1 m/s in the test piece (Figure 8(a)). During the next 45ms the sliding velocity decayed in four discernable 'steps' (which are probably an artifact of the helix in the tendon strand) through 4,7m/s, 4,3m/s, 3,2m/s, 2,7m/s to zero after 150mm of slip.

The second impulse of 1,03kJ (Figure 8(b)) caused the tendon to start sliding at 7,7m/s then slow to 3,8m/s after some 60mm displacement, before accelerating to 6,3m/s after a further 44mm. This accelerating final rate resulted from the complete pulling out of the tendon.

In most tests the velocity profile was much simpler and sometimes less precise. The flexible wire link between the lower end of the specimen and the recorder pen was provided with a short multi-strand link of Kevlar line to prevent damage to the recorder when the test specimen failed and the swing beam dropped freely onto the lower stop block. Sometimes this safety link snapped prematurely due, presumably, to shock loading at impact and no trace, or an incomplete velocity profile, was obtained.

Altogether, some 53 usable velocity profiles were obtained: four velocity values were over 20m/s, five were over 15m/s and seven were between 10 and 15m/s. All of these recorder traces were re-examined and found to consist of good data.

3.5 System stiffness

In the first test, the rebar specimen and swing beam were suspended from the same superstructure that had supported the cladding specimens throughout the GAP 221 programme. After 12 small energy impulses totalling 25kJ had caused 25mm of elongation and a further heavy impulse of 5kJ still failed to break the bar, it became clear that there was some resilience (bounce) in the system and that the 'sharpness' of impulsive load necessary to cause rupture, would not be achieved.

During the following 7 weeks the testing facility was re-designed and substantially modified. Greatly increased stiffness was achieved essentially by using heavier, stiffened double-channel beams supported on four pillars of concrete-filled heavy-duty 250mm diameter steel pipes positioned so as to reduce the bending span from 2,7m to 0,4m. Figure 9 shows the

stiffened structure. The softest element in the modified assembly was the 90mm diameter pivot bar, which has a calculated stiffness of 1,4MN/mm and an ultimate strength of 1900kN.

The first test after the system stiffness had been improved (by perhaps two orders of magnitude), also did not break the bar. It revealed valuable additional insight into the dynamic response of tendons as well as into the methodology requirements of the testing procedure.

The first impulse of 2,0kJ caused 15mm of elongation across the separation surface where the two tubes of the test holder had been butted together. A second impulse of 4,4kJ caused 42mm of additional elongation but again failed to break the bar.

It appeared that the first impulse imparted to a re-bar which is fully-bonded across a discontinuity must not only be 'sharp' enough but must also be large enough to exceed the

critical value in order to break the bar at the first impact. A smaller amount of elongation has two simultaneous effects that 'soften' the blow and prevent failure. Firstly, there is some work-hardening that toughens the steel and, secondly, a certain amount of de-bonding will have occurred that then allows the elongation strain to be distributed along a greater length of the tendon.

There is little doubt that continued impulses of similar or even larger energy input would have continued the process of stretching the bar along a progressively increasing de-bonded length without causing rupture, as was the case in test No. 1.

It later became evident that this phenomenon was to be found in most of the other tendon types as well.

Thus it is clear that it is only the 'first drop' impulse that can be validly used to 'bracket-in' to the determination of the critical value. The procedure that was consequently followed was to commence the testing of a particular tendon type with a first impulse that would be certain to be considerably in excess of the critical value of rupture energy so that rupture would definitely occur. The second impulse would then be imposed at one-half the first value. If failure occurred then the third impulse would be one-half as much as the previous and so continued until the tendon did not break. The following impulse would then be increased by one-half the difference between the previous two energy values. In this way a succession of tests, on identical specimens, would 'bracket in' to a final approximate value that would be taken as the design value for the rupture energy of the tendon.

With certain types of tendon, failure by rupturing cannot occur or is normally most unlikely to happen. Their retention effect is developed by frictional resistance to sliding where energy is dissipated mostly by heat. To a greater or lesser extent additional energy may be absorbed in ductile elongation of the steel of which the element is made. In such cases, the amount of energy consumed could roughly be calculated from a simple tape measurement of the amount of slip or elongation induced by each successive energy impulse.

3.6 Distribution of energy

Underlying the conceptual basis of the testing method is the assumption that one-half of the energy imparted to the mid-point of the swing beam by the impact of the drop weight would go into stressing the tendon under test, while the other half would be lost in the pivot bar.

When it was discovered initially just how difficult it was to break rebars, one possibility that was considered was that a much smaller fraction than half of the energy was stressing the test specimen while the majority of the energy was being attracted to the very stiff element, viz the pivot bar. In order to test this possibility, a limited number of experiments were performed with the pivot bar substituted by a second test piece in parallel with the first. These twin-parallel tests are referred to as 'tandem' tests in Series 1 and Series 2. Because the 'eye' of the shepherd's crook was large enough to accommodate the pivot pin, the modification was relatively simple to put into effect.

Figure B2 and Figure B3 in Appendix B show that there was no large or consistent bias in the energy distribution. Generally, the initial response was that the eastern specimen consumed more energy while later, in the succession of small impulses that constituted a test, more energy appeared to go into the western twin (which would normally be the pivot bar). The fact that values obtained from the single bar tests showed very similar trends and characteristics to those of the means of values yielded by the 'tandem pair' gave considerable reassurance that the rationale underlying the test methodology and the interpretation and analyses of the data was valid and appropriate.

4 Results

The essential details of all the tests in the six series are assembled in tabular form in Appendix A. The design values derived from these tests are summarised in Table 1 for ease of reference and quick comparison.

All the valid data from which design values were obtained are summarised separately in Tables 2 to 7 for the different types of tendon.

More detailed discussion of the individual results and their practical implications are given in the Sections 4.2.1 to 4.2.6 that follow.

Understanding of these detailed discussions will be made simpler by first considering, in a broader context, the ways in which impulsive energy can be absorbed or dissipated.

4.1 General discussion

When a fully grouted tendon is subjected to an impulsive load at a separation surface, it can absorb energy in three different ways:

- If the tendon is strongly bonded or otherwise totally prevented from slipping (as eg in the case of re-bar or pre-stressed cable) then 'necking' will commence at the separation surface. The resulting reduction in diameter causes a stress concentration which, because it is localised at this point, drives the 'necking-down' process to proceed rapidly and unstably to complete fracture with the classic 'cup-and-cone' appearance. Because of the small volume of steel which is undergoing plastic deformation, the total energy consumed is relatively little. This is the energy component which is denoted as **rupture energy** in Table 1.
- If failure of the bond at the grout/steel interface takes place and slip can commence (as in the smooth bar) then an interesting phenomenon occurs. Necking will commence and some energy will be consumed in the resulting plastic deformation which, at the same time, causes work hardening. There is no localisation of the stress concentration which instead progresses along the length of the tendon as the onset of necking forces the breakdown of the bond to also continue along the tendons length. The process will proceed in both directions away from the point of initiation until, theoretically, virtually the whole length of tendon is involved. Failure of the steel bar will not occur and relatively large amounts of energy will be absorbed. The amount of energy consumed is directly proportional to the amount of stretch - Figure 13.

This is the energy component designated as **elongation energy**.

- A small decrease in diameter of the solid steel accompanies the above progressive elongation of the smooth bar. This causes the grout/steel bond to break down and permits sliding to take place. Energy is consumed, presumably largely in the form of heat, against frictional resistance. In the case of a splitset or Swellex, the fact that the steel tube is hollow makes it relatively easy for the pressure normal to the interface to relax sufficiently to allow sliding to take place. This sliding resistance is essentially the only form of energy consumption in splitsets, and in Swellex when the embedded length is less than the minimum (1400mm) required to prevent sliding and invoke rupture.

This is the energy component denoted as **sliding energy**.

With smooth bar shepherds crooks, the relative amount of energy dissipated in elongation and in sliding, depends on the embedded length. With longer embedded lengths (probably in excess of 1,5m) all of the energy would initially be consumed in the form of elongation energy until de-bonding has progressed far enough for the yield force causing the elongation, to become larger than the decreasing bond strength of the remaining unelongated portion of the bar.

Thereafter sliding will commence at a lower but indeterminate rate and the amount of additional energy consumed in elongation will tend towards zero. This aspect is discussed more fully in Appendix C.

In a 16mm diameter bar, nearly 14kJ will have been absorbed for each 100mm of elongation or permanent stretch that occurs before the onset of sliding.

Once sliding is taking place so easily that no further elongation is possible, the rate of energy dissipation through friction will depend on the length of tendon still embedded and will decrease directly as the embedded length decreases. In the other tendon types where breakdown of the grout bond is possible similar energy-absorbing processes will occur. All will be conditional on the tendon being substantially straight in a hole that has not been 'dislocated' by any transverse shearing displacement.

Table 1
Summary of design values for various rock tendons

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Test Series	Tendon Type	Rupture Energy kJ	Elongation Energy kJ/100mm	Sliding Energy kJ/100mm
1	Rebar 16mm	4,8 ± 0,7	-	-
2	Smooth bar 16mm	-	13,9	3,0 x l _{ej} - 0.15*
3	Vaal Reefs hoist rope strand	< 2,4	-	0,8 to 8,2
4	18mm compact strand cable	17,5 ± 2,0	-	-
5	39mm diameter splitsets	11,6 to 15	11,6 ± 1,3	3,0 to 6,3
6	Standard Swellex	4,6 ± 0,5	9,9	3,0 to 5,8

* l_{ej} is initial embedded length in metres

4.2 Individual results : Discussion and practical implications

4.2.1 16mm diameter rebar

After the initial tests had been conducted (see results of tests 1a, 1b, 2 and 2a in Table 2) and the test frame had been properly stiffened, the remaining rebar tests showed a rational progression from **fracturing** at higher impulsive loads (with the amount of elongation decreasing as loads decreased), to **stretching** without failure, at input energy of less than 4kJ. These later results are shown for tests 6, 9 and 11 in Table 2 in which the rebars were broken and test 10 of Table 2 and in test 13 of Table 2(a) where the tendons did not break.

Table 2
Tests on 16mm diameter rebar shepherds' crooks

Series 1: Rebar shepherds' crooks, 16 mm diameter					
Test No	Embedded length (m)	Input energy (kJ)	Elongation (mm)	Theoretical energy consumed* (kJ)	Remarks
1(a)	0,6 nom.	0,35	5,0	0,56	25 mm of stretch caused by several earlier small impulses, caused some work-hardening
1(b)	0,6 nom.	5,14	40	4,5	
2	0,6 nom.	2,0	15	1,7	First impulse insufficient to break rebar - instead causes some work hardening and some debonding
2(a)	0,6 nom.	4,4	42	4,7	
6	0,6 nom.	15,4	95	10,7	Rebar broke
9	0,6 nom.	7,7	50	5,6	Rebar broke
10	0,6 nom.	3,8	36	4,1	Rebar did not break
11	0,6 nom.	5,8	38	4,3	Rebar broke
* From manufacturer's laboratory test, yield strength = 112,6 kN Energy consumed in stretching bar equals 112,6 x elongation (m) = kJ					

Design value: Rupture energy = 4,8 kJ (mid-value between tests 10 and 11)

The graphs in Figure B1 in Appendix B show the energy input plotted against a calculated 'energy consumed' which is simply a function of the amount of elongation resulting from successive energy impulses. The elongation value multiplied by the static load corresponding to the yield stress of the rebar steel (from the supplier's quality assurance test certificates) gives a value for the energy that would have been consumed in stretching the bar to its fracture limit if the actual transient force was constant over the distance stretched and of the same value as the static yield force in the laboratory. The fact that the graphs are linear and pass through the origin shows that a systematic response is being induced by the testing apparatus with reliability and repeatability, and monitored with adequate precision.

The mode of failure induced was similar to that often seen underground, with fairly abrupt 'necking' and ragged-edged rupture - see Figure 10.

The phenomenon of 'protective softening' as a result of progressive debonding, already described in Section 3.4, was demonstrated by test Nos 2 (see Table 2) and 13 (see Table 2(a). **In each case the first impulse was less than the critical rupture energy and the total energy input was considerably greater, yet the bars did not break.**

The progressive nature of the debonding was exposed and measured by sawing through the test piece of test No 6. Here a 15 kJ impulse caused 95mm of elongation which was accompanied by 190mm of de-bonding of the embedded length, as shown in Figure 11.

Table 2 (a)
Tests on pairs of 16mm diameter rebar shepherds' crooks

Series 1.1: Rebar shepherds' crooks in tandem					
Test No	Embedded length (m)	Input energy (kJ)	Elongation (mm)	Theoretical energy consumed* (kJ)	Remarks
13	0,6 nom.	3,8	24	2,7	East bar. Did not break
		3,8	15	1,7	West bar. Did not break
13(a)	0,6 nom.	6,7	35	3,7	East bar. Did not break
		6,7	33	3,9	West bar. Did not break
* From manufacturer's laboratory test, yield strength = 112,6 kN Energy consumed in stretching bar equals 112,6 x elongation (m) = kJ					

Design value : Rupture energy = 4,8kJ (from Table 2)

There can be little doubt that the protective effect of progressive debonding occurs as a rule rather than as an exception in most deep level tunnelling conditions in the gold mining industry. The prevalence of fracturing around the tunnel provides the opportunity for progressive debonding to initiate at many points along the length of the bar. It must be remembered that these conditions also expose the bar to corrosion. However, there are many instances where bolt rupture can occur, for example, where larger joint blocks or wedges act

'en masse' on a fully grouted bar traversing the joint surface which separates the block from the solid rock mass beyond. Thus, it would be inadvisable to use a design value of more than 4,0 kJ per bolt in design calculations.

4.2.2 16mm diameter smooth bar

Because there is no positive anchoring device in the smooth bar shepherds' crooks, sliding and elongation of the straight smooth shank can take place separately or at the same time and in varying degrees, as indicated by the results in Table 3(a). This variability is shown in the graphs of Figures B2 and B3 in Appendix B. In Appendix C an attempt is made to rationalize this variability by developing a model based on parameters describing the onset of ductile behaviour in steel and the build-up of shear resistance across a steel/cement bonded interface. From this approach conservative design values are estimated.

Rupture energy

In order to gain some idea of the energy that would be consumed by stretching and rupturing of the smooth bar if the embedded length was prevented from sliding (eg as a result of partial transverse shearing of the hole) four separate tests were carried out on smooth bars of 1560mm grouted length (of which 960mm was the embedded length) and whose ends were threaded and secured by spherical seats and nuts against flat plates at the ends of the heavy steel tube test pieces. Failure in the threads at the first impulsive load on tests 52 and 54 and during the second impulse on tests 51 and 53 limited the valid data to the two results of Table 3. Failure did not occur at mid-length where it was intended so no indication could be obtained of the rupture energy of smooth bar. However substantial elongation was evident across the separation surface in test 51 and 53. Dividing the energy impulse value by the corresponding amount of stretch yielded energy consumption rates of 11,7 and 11,0kJ per 100mm which was all associated with ductile elongation since no slip was possible.

Table 3

Tests on 16mm diameter smooth bar shepherds' crooks

Series 2: Smooth bar shepherds crooks, 16mm diameter					
Test No	Embedded length (m)	Input energy (kJ)	Elongation (mm)	Elongation energy* consumed (kJ/100mm)	Remarks
51	0,96	15,4	132	11,7	Some 'necking' occurred at mid-length and probably also in threads so total elongation was increased and therefore rate of elongation energy consumed is probably somewhat underestimated.
53	0,96	10,3	94	11,0	

* Consumed energy (normalized to 100mm of displacement) is derived on the basis that amount of elongation is initially simply proportional to the amount of energy input - see Appendix C.

Derived value : Elongation energy = 11,3kJ per 100mm (mean of #51 and #53)

Considering the probable under-estimation mentioned in the remarks above, these results agree reasonably well with those derived from the 'tandem' tests in Table 3(a)

Sliding energy

Most of the shepherds crook smooth bars that had been prepared as 'pull-out' test specimens were tested as 'tandem pairs' for the ancillary purpose described in 3.6 (p8). In order to gain some indication of the relative effectiveness of the two different forms of energy consumption viz sliding and elongation, the slippage of the upper end of the embedded length was separately measured in tests 15,16 and 17 so that the actual amounts of stretch and sliding could be identified. In test 16, the initial embedded length of 1,9m was sufficiently long to prevent any sliding during the first two impulses of 10,3kJ which each caused 74mm of elongation and consumed energy at a rate of 13,8kJ/100m. Once slip commences the amount of energy consumed in elongation reduces and more is lost in frictional sliding.

The results are given in Table 3(a).

Table 3(a)
Tests on pairs of 16mm diameter smooth bar shepherds' crooks

Series 2.1: Smooth bar shepherds' crooks in tandem								
Test No.	Embedded length before drop (mm)		Input energy (kJ)	Elongation (mm)		Slip (mm)		Remarks
	East	West		East	West	East	West	
14	600	600	10,3	450	95			Slip part of displacement not measured, probably very considerable on East bar
15	915	911	8,2	37	22	25	3	The graphs in Figure B2 show that the displacements after the second impulse were largely due to sliding. This permitted a reliable estimate to be made of the energy consumed by sliding - Appendix C.
15(a)	890	908	4,1	51	40	56	10	
15(b)	810	788	4,1	54	51	82	56	
15(c)	859	901	4,1	54	64	105	123	
15(d)	833	855	8,2	57	87	145	373	
16	1921	1900	10,3	47	27	0	0	Figure 13 gives a plot of elongation and slip components of displacement as a function of cumulative total energy, for tests 15 and 16. In test 15, some slipping occurred from the start, in # 16 slip commenced only after 20kJ of energy input.
16(a)	1921	1900	10,3	73	75	0	0	
16(b)	1921	1900	5,1	73	103	18	0	
16(c)	1903	1900	5,1	71	124	57	2	
17	600	600	6,2	?	?	>500	?	Embedded length too short- East bar pulled completely out on first drop.

Derived values :elongation energy = 13,9kJ per 100mm

slip energy = $3,07l_{e_1} - 0,15$ per 100mm slip

Note: If the initial embedded length(l_{e_1}) is known in metres the above estimate of slip energy consumed can be used as a design value, but not in a simple straightforward way. The conceptual model from which the estimates were derived is valid and has been shown to be self-consistent (Appendix C). However it shows

that the frictional resistance depends on the area of the interface between tendon and grout. Therefore the resistance must decrease with decreasing embedment length - essentially an unstable process. Thus the slip energy relationship quoted above should not be used for the determination of design values for tendons which rely purely on frictional resistance, without a complete understanding of their very real limitations.

Depending on the effective embedded length, either or both energy-absorbing components can be involved in the response to a single impulsive load.

In principle, the relative contribution of the two modes of energy loss will be determined by the length of tendon which remains embedded in the rock mass. Because a significant change in embedded length can take place during the course of a single impulse, the process is complex and intrinsically indeterminate.

In general, elongation is considerably more effective in consuming energy than slip. For example in test #16 while slip at the remote end of the bars was prevented by their average embedded length of 1,91m, all the energy can be said to have been consumed in elongation. At the third impulse the east bar had commenced slipping and the constant rate of energy consumption which characterized the elongation process had started to decrease - see Figures 13 and B3.

In test #15 the same general behaviour is evident but, because of the shorter initial embedded length, important differences are apparent. Figures 13 and B2 show that some sliding occurred with the first impulse in both bars, on average contributing one-half as much to the displacement as the elongation. Thereafter sliding rapidly became the dominant mode of displacement, so much so that, after the fourth drop, the average rate of sliding was 12 times greater than that of elongation. These observations in tests #15 and #16 made it possible to formulate a model which enables the amounts of elongation energy and slip energy consumed, to be estimated with reasonable reliability. Table 1 in Appendix C compares the amounts of elongation and of slip estimated from the model with those measured in tests #15 and #16.

The fact that the elongation energy consumption rate is the same for an average embedment length of 1910mm as it is for 913mm suggests that it is independent of embedded length. If this constancy of rate is maintained it follows that **a smooth bar cannot be broken no matter how long it is or how much impulsive energy is imparted to it** provided that the hole is straight.

If this argument is valid it obviously has important implications for the design and manufacture of yielding support units and also for the design of a support system which is based on the use of smooth bars.

This phenomenon of progressive de-bonding causing an ever-increasing length of bar to become available for stretching and permanent elongation, is potentially a very useful means of dissipating energy and at the same time, protecting the tendon from overload and abrupt failure. It was first observed by Pells (1974 : 1216) and Ortlepp (1983 : D184) who advanced the explanation that it resulted from progressive 'necking', de-bonding and workhardening.

In order to utilize the benefits of progressive debonding, it is necessary that the embedded length should be adequate – 0,9m embeddment is too little, while 1,9m is probably more than adequate. Appendix C gives an example of how the necessary embeddment length can be calculated.

No design value is given for the rupture energy because, in a straight hole, it appears from the foregoing theoretical argument and from experience during the testing, that it is very difficult to break a fully grouted smooth bar. Further testing of how much dynamic energy can be absorbed before fracture occurs is clearly necessary. On the other hand, as with friction-anchored tendons, there are serious uncertainties associated with the use of smooth bars that have inadequate or marginally adequate embedded lengths or where the cementitious grouting is not properly done.

4.2.3 Grouted rope strand

Of the nine rope specimens initially prepared, only five gave useful results, as shown in Table 4. The first three tendons had embedded lengths of 1400mm but little was learned about whether this was sub-critical or super-critical because ferrules failed or the loop flattened completely and disappeared up the hole. The latter effect is said to occur quite commonly in practice and effectively amounts to a 'protective' device which prevents rupture of the tendon but, at the same time, masks other inadequacies in the overall system behaviour.

When they are installed, the rope 'strand' tendons are still coated to a greater or lesser extent with rope dressing from the original intact winding rope. The result is that, despite the residual helical shape, the tendon slips more easily and more erratically than the smooth bars of Series 2.

Because the embedded lengths were somewhat shorter than the thick-walled steel tubes in which they were grouted the end of the rope was not accessible. Consequently the amount of

slip could not be measured separately. The total displacement plotted against energy input in Figure B4 therefore includes an amount of elongation which is unknown but which is believed to be small. The effect of this will not be small even if the displacement is only 5 to 10mm, because the yield force is large since the wires of the original hoist rope are of ultra-high tensile steel.

When subjected to the dynamic loading of a rockburst, rupture of the tendon occurs only very infrequently. In order for rupture to happen, the embedded portion must somehow be 'locked-in' somewhere near its embedded end presumably by partial dislocation of the hole deep within the rock surround. To determine what the rupture load would be in such circumstances, four additional specimens were prepared with double-ferruled loops at each end. The 960mm bonded length was thus effectively end-anchored and was relatively easily broken close to the separation surface where the test holders were abutted. The results of these tests are shown in Table 4(a).

Table 4
Tests on grouted rope strand

Series 3: Grouted rope strand: Sliding resistance					
Test No	Remaining Embedded length (mm)	Input energy (kJ)	Cumulative Slip (mm)	Frictional energy consumed (kJ/100mm)	Remarks
18	798	15,4	610	2,5	Entire slip came from embedded length
19	798	2,06	33	6,0	With each impulse, relaxation of helix caused bottom holder to rotate anti-clockwise about 25°. Each successive load increment (after 80mm) caused rapidly increasing amount of slip
19(a)	765	2,06	58	8,2	
19(b)	740	2,06	83	8,2	
19(c)	715	3,08	183	3,1	
19(d)	615	3,08	373	1,6	
21	395	1,03	33	3,2	Much shorter initial embedment length resulted in much greater successive increments of slip than No. 19
21(a)	362	1,03	63	3,4	
21(b)	332	1,03	170	0,96	
21(c)	225	1,03	?	-	
22	405	1,37	180	0,76	Rope pulled out completely
22(a)	225	1,03	?	-	
30	798	5,14	391	1,3	Slip might have been greater - swing beam was arrested

Design values :

Sliding resistance energy : Initial bond length of 400mm :- **0,76 to 3,4 kJ/100mm**

Initial bond length of 800mm :- **1,3 to 8,2 kJ/100mm**

Note: A conservative design dictates that the lower values should be used in any formal design procedure.

For a particular tendon the dynamic resistance to sliding is strongly dependent on the initial embedded length and, if load is repeated, on the embedded length remaining at any particular stage - see Figure B5.

There can, however, be large differences between individual tendons probably reflecting different amounts of rope dressing (lubricant) remaining on the strand. This is evident in the non-uniform decrease in the

values of frictional energy consumed in Column 5. Because the initial sliding resistance was so clearly determined by the initial embedded length, two ranges of values are indicated as design values in Table 4.

Figure B4 shows the dependence on embedded length, broadly, by comparing the 800mm embedded length of test No 19 with the much lower sliding resistance of the 400mm embedded lengths of test No 21. Also there is a roughly systematic reduction in unit resistance evident in test No 19 as the remaining embedded length reduces from 800 to 600mm - Figure B5.

When subjected to the dynamic loading of a rockburst, rupture of the tendon occurs only very infrequently. In order for rupture to happen, the embedded portion must somehow be 'locked-in' somewhere near its embedded end presumably by partial dislocation of the hole deep within the rock surround. To determine what the rupture load would be in such circumstances, four additional specimens were prepared with double-ferruled loops at each end. The 960mm bonded length was thus effectively end-anchored and was relatively easily broken close to the separation surface where the test holders were abutted. The results of these tests are shown in Table 4(a)..

Table 4(a)
Tests on grouted rope strand

Series 3.1: Grouted rope strand: Rupture energy				
Test No	Remaining embedded length (mm)	Input energy (kJ)	Elongation (mm)	Remarks
55	960	19,5	-	Strand broken abruptly 30 mm into bottom holder
56	960	9,8	-	Broken 370 mm into bottom holder
57	960	4,9	-	Broken 20 mm into bottom holder
58	960	2,4	-	Broken 25 mm into top holder

Design value : Rupture energy = less than 2,4 kJ

- Note:** i) In practice the rupture energy is probably seldom invoked because the tendon is very difficult to break due to the ease with which it slips.
 ii) For the above reasons the behaviour of grouted rope slings must be regarded as erratic. Design values cannot be used in rational design procedures, but only as very crude indicators of the effectiveness of the system as a whole.

The rupture occurred with insignificantly small elongation probably because of the inherently low ductility normally associated with the very high UTS of the hoist rope wire. The lowest

'bracketing' impulse applied, viz 2,4kJ, was still sufficient to cause rupture, so the actual limiting rupture strength value was not observed.

Paradoxically, tendons of this type actually have a lengthy history of reasonably good performance on at least two large mines. Intuitively, the characteristics measured in these tests would suggest that most of the rockburst damage on these mines must have been of relatively low intensity. Theoretically it would seem that rope slings are fundamentally unsuitable as support against moderate or severe rockbursts because of the very low value of rupture energy and the somewhat erratic values of sliding resistance when the embedded length is short.

4.2.4 18mm diameter, 400kN pre-stressed cables

The tests carried out on 18mm diameter steel cables pretensioned to 25 tons are summarized in Table 5. One test performed on a 15 mm diameter yielding cable is presented in Table 5(a).

Table 5

Tests on 18mm diameter pretensioned steel cables

Series 4:18 mm steel cables (pre-tensioned to 25 tons)					
Test No	Embedded length (mm)	Input energy (kJ)	Elongation (mm)	Indicated 'strain' velocity (m/s)	Remarks
32	1500	19,9	42	2,0	Cable broke. 'Cup-and-cone' fracture of all strands.
33	1500	10,3	12	1,8	Cable did not break
33(a)	1500	15,4	95	-	
34	1500	15,4	29	-	
39	1500	9,9	21	6,8	Cable did not break
40	1500	14,9	49	6,4	Cable did not break
40(a)	1500	4,0	51	6,2	
40(b)	1500	4,0	52	3,7	Significant energy consumed with very little additional elongation
40(c)	1500	4,0	53	2,1	
41	1500	19,9	10	4,0	Cable broke in same manner as no. 32.

Design value : Rupture energy = 17,5 kJ (mid-value between #41 and #34)

Note: i) In test #40 a smaller initial impulse (14,9kJ) caused significantly more elongation (49 mm) than in test # 34 where 15,4 kJ produced only 29 mm elongation. The larger drop weight of 2706kg was used in #40 which produced a 'start velocity' of 140 m/s compared with 80m/s in #34.

The very high tensile strength of the wire from which the 'compact strand' is manufactured would suggest that, like the de-stranded rope sling, there would be very little ductility to absorb energy by way of plastic elongation. In fact, there was very little visible indication of necking at the broken ends, and 'cup-and-cone' fracturing was near perfect and very abrupt in appearance - see Figure 12. Since these cables are always installed with mechanical type end anchors, there is no chance of slippage occurring, so sliding resistance energy is not invoked.

Notwithstanding these constraints and observations, the results gave strong indications that the tightly-enveloping grout annulus somehow makes it possible for more elongation energy to be absorbed on occasion than would be expected. Under identical conditions, test Nos 32 and 41 each experienced decisive failure at the same impulsive load of 19,9kJ. A distinctly different response was observed in test No 33 where an initial impulse slightly more than one-half as large produced, as might have been expected, a proportionately much smaller elongation of 12mm. A second substantial impulse, giving an accumulated energy input of 25,7kJ, almost 30% larger than the critical failure load, did not break the tendon but merely stretched it an extra 83mm. Test No 40 behaved in similar fashion, absorbing 35% more energy than the critical 'first impulse' value. The graph in Figure B6 shows that the extra strain accompanying the successive load increments was very small but that it increased as a smooth progression. Thus it seems that progressive de-bonding and elongation of the kind occurring in smooth bar plays a role in cables as well although it is smaller and less obvious.

Prestressing reduces the energy-absorbing capacity of fully grouted cables. It is appreciated that a certain amount of residual tensile strain is necessary to keep the tapered wedges in position in the boss at the collar of the hole. However, any prestress tension beyond this minimum value is not desirable since it can only diminish the total energy absorbed before failure.

An effective yielding mechanism would increase the value of long cable anchors very considerably. Innovativeness on the part of the manufacturers should be strongly encouraged.

The one test yielding cable supplied by the manufacturer, was unsatisfactory because of a premature failure of the clamping wedges at the lower collar - Table 5(a).

Table 5(a)
Yielding steel cable

Series 4.1 15mm yielding cable					
Test No	Embedded length (mm)	Input energy (kJ)	Yield (mm)	Indicated 'strain' velocity (m/s)	Remarks
42	N/A	6,6	29	3,1	Rate of energy absorbed is 23 kJ/100mm
42(a)	N/A	6,6	?	3,3	Tendon failed at bottom collar where one wedge slipped

4.2.5 39mm diameter splitsets

Although a great deal of careful thought, painstaking attention to detail and physical effort went into the attempt to simulate a realistic borehole in 'synthetic rock', the final results were not successful. A great deal was learnt which is no doubt qualitatively applicable to the behaviour of splitsets in actual underground service. Quantitatively, however, it cannot be claimed that the observed behaviour is representative of real life. Because actual underground behaviour is likely to be so variable, even erratic, it must extend over a large range of resistance values some of which would indeed be similar to those observed in the tests.

Since the original objective had been to try to determine the rupture energy, the splitsets were longer than normal. It was thought that 2,4m embedded length might resist being pulled out to the extent that the tendons would break instead. When it became apparent that the very long tendons could not be installed, certain stratagems were resorted to. An epoxy adhesive provided initial lubrication which made installation possible and it was hoped that it would also simulate the corrosion and initial distortion that the manufacturers claim would improve the pull-out resistance. In this respect the epoxy failed to achieve the desired effect and, at the same time, introduced an indeterminate change in the friction characteristic of the rock/steel interface. As is evident in the graph shown in Figure B7, the cumulative slip in test No 37 varies smoothly and systematically with increased energy input, and back-extrapolation would intersect the zero slip axis at about 1,5 kJ which could be the bond strength of the epoxy. Also, the unit rate of energy consumption is considerably less than that of the tendons in test Nos 48, 49 and 50 (see

Table 6(a)), where the ends were deliberately fixed and only stretching was possible. Thus, the behaviour is rational and no doubt displays qualitatively how the steel tube of the splitset would unlock itself in a straight hole, even where there is a slightly corroded steel/rock interface. However, the quantitative value of the sliding resistance appended to Table 6 cannot be regarded as necessarily realistic.

The results are given in Table 6.

Table 6
Tests on 39mm diameter splitsets

Series 5: 39mm diameter splitsets: Sliding resistance					
Test No	Embedded length (mm)	Input energy (kJ)	Slip (mm)	Energy consumed in sliding kJ/100mm	Remarks
36	1600	7,7	256	3,0	Approx. 400mm epoxy-bonded. Valid test - all slip came from top
37	2370	7,7	98	7,8* (6,3)	Approx. 1400 mm epoxy-bonded - Valid test - all slip came from top.
37(a)	2272	1,03	117	5,4	*Includes energy to break epoxy adhesion, estimated to be 1,5kJ - by extrapolation of the graph in Fig. B7
37(b)	2253	1,03	138	4,9	
37(c)	2232	1,03	161	4,5	
37(d)	2209	1,03	185	4,3	

'Design' value : Sliding resistance : For 1,6 m embedded length : **3,0 kJ/100 mm**

– decreasing

For 2,4 m embedded length : **6,3 kJ/100mm**

– decreasing

Cautionary notes:

- i) Extrapolation of these values - Figure B8 - indicates that dynamic resistance could be low as 1,0 kJ/100 mm for an embedded length of 1,0 m in a drillhole of 36,5 mm diameter
- ii) Sliding resistance is obviously very sensitive to diameter of drill hole - therefore could be significantly below 1,0 kJ/100mm. Before using the above resistance values in a formal design procedure it would be prudent to determine pull-out resistance in a range of rock types and for a series of carefully measured hole diameters in a narrow range of diameter steps.
- iii) Very strong discipline has to be instituted over the installation crew in regard to constant checking of drill steel gauge.

In order to gain some idea of the energy that would be consumed by stretching and rupturing if the remote end of the splitset was clamped by partial dislocation of the hole and the collar ring did not fail, splitsets were made to protrude slightly beyond the ends of test-piece holders 1,2m long. By means of tapered conical wedge plugs and double square-domed face-plates, three splitsets were effectively end-anchored - tests No 48, 49 and 50. One of these, test No 49, broke at the correct mid-point on first impulse, at a value of 15,4 kJ. The splitset in test No. 48 was subjected to a first impulse of one-half that value which seemingly invoked the progressive debonding, energy-enhancement phenomenon already discussed. A further 6 impulses imparting a total of 26,7kJ and 205mm of elongation, were delivered before rupture eventually occurred at the desired plane of separation. This was about twice as much as was required for the first-impulse break. Test No. 50 did not break at the desired place, but it also consumed significantly more energy from repeated impulses than the critical, 'one-hit' impulse load.

These results are shown in Table 6(a).

Table 6(a)**Energy consumption tests on 39mm diameter splitsets**

Series 5.1 : 39mm diameter splitsets: Energy consumed by elongation and rupture					
Test No	Embedded length (mm)	Input energy (kJ)	Elongation (mm)	Energy consumed in stretching kJ/100mm	Remarks
48	960	7,7	74	10,4	Did not break Abnormally high value disregarded in determining mean
48(a)	960	1,0	77	33,33	
48(b)	960	2,6	99	11,8	
48(c)	960	2,6	120	12,2	
48(d)	960	2,6	140	12,8	
48(e)	960	5,1	186	11,2	
48(f)	960	5,1	205	?	
49	960	15,4	110	14,0	Broke at separation plane Valid test
50	960	11,6	102	11,3	Did not break
50(a)	960	2,6	122	13,0	Elongation energy very similar to test no. 48.
50(b)	960	5,1	167	11,3	
50(c)	960	5,1	?	-	Broke at wedged end - not valid for rupture estimate

Design values :

Rupture energy : between 11,6 kJ and 15 kJ (mid value of test no's 49 and 50)

Elongation energy : 11,6 ± 1,3 kJ (mean of tests 48 and 50, excluding 48(a))

- Notes: i) This relatively high rupture value is of academic interest only. In a straight hole, sliding will occur at a much lower value which will be strongly dependent on:
- diameter of hole
 - embedded length beyond plane of potential separation
 - amount of corrosion
- ii) The very high elongation value (compared with eg. smooth bar) occurs only because the 'hollow' construction of the splitset allows it to be drawn away from the walls of the hole and progressively distribute the ductile stretching along the entire length of the tendon.
- iii) This value for elongation energy is also not realistic under actual operational conditions. Normally splitsets would slip and not stretch unless some dislocation in the hole prevents sliding. In that case, failure of the splitset would commence at the sharp edge of the

dislocation and it would be torn apart at much lower values of energy.

The graphs of Figure B7 show identically similar elongation response to the repeated impulsive loading for splitsets in tests Nos 48 and 50 indicating that the test procedure is repeatable and reliable.

4.2.6 Standard Swellex

In a uniform, straight hole in good synthetic rock, it proved impossible to break the Swellex tube at the separation plane. With embedded lengths of 1,4m or less, slip occurred with only small amounts of elongation. With longer embedded lengths, the welded-on ferrules that support the face plates at the end of the Swellex tube failed repeatedly, even after these had been reinforced.

In order to gain some idea of the rupture strength potential of Swellex if the defect at the ferrule end was eliminated, four specimens with 960mm embedded length were set in an annulus of Capram grout in the split tube holders. The ferrules were reinforced with 6mm diameter mild steel rod spirally wrapped around the ferrule, with light track welding joining adjacent winds of the wrap. This device was successful in locking the collar end of the Swellex in test #46 and #47 but, specimens #44 and #45 failed by shearing the weld that sealed the crimped end of the tube and joined it to the ferrule.

In order to prevent slipping of the upper embedded length, the end of the tube was allowed to project a short distance beyond the top of the specimen holder where it formed a bulge on inflation that locked it completely. From the two successful tests it appeared that an impulse of between 4,1kJ and 5,1kJ would be necessary to cause rupture of a Swellex locked-in some 1,4m above a separation surface.

Where the embedded length was substantially greater, as in test #28 and #38, slip did not occur and energy was consumed by elongation.

Where the embedded lengths were less than 1,4m, displacement took place mainly by slipping, to the extent that it was assumed to be the dominant mode of energy dissipation and could therefore be used as the basis for the calculated value of energy consumed, in Table 7.

The test results are given in Table 7.

Table 7

Tests on standard swellex bolts

Series 6: Standard Swellex						
Test No	Embedded length (mm)	Input energy (kJ)	Slip/elongation (mm)	Energy* consumed kJ/100mm	Result	Remarks
23	1390	7,7	0/42	18,3 rupture	Broke	Inflated tube was locked into hole by a 'hernia' about 500mm from joint. Clean tensile fracture
24	1390	3,8	65/9	5,8	No break	74 mm gap includes 9mm stretch. No further stretch 4mm further stretch
24(a)	1325	2,6	120/9	4,7	No break	
24(b)	1270	6,4	332/13	3,0	No break	
25	1390	5,8	99/11	5,9	No break	Embedment length not adequate to prevent slip. Some work-hardening prevents break at next impulse and further slip occurs.
25(a)	1291	1,5	129/11	5,1	No break	
25(b)	1261	1,5	160/12	5,0	No break	
26	1390	10,3	285/0	3,6	No break	No stretch. Confirmation that 1390mm embedment is inadequate
27	2390	2,6	?	-	No break	Failure of collar at 1st impulse - no slip at top
28	2390	3,6	0/39	9,1 elongation	No break	Failure of ferrule weld after 2nd impulse
38	1910	5,1	44	11,7	No break	No slip measured
38(a)	1866	1,5	60	9,6 elongation	No break	- all elongation
46	960	5,1	55	9,3	Broke	See photograph in Figure 13. Valid test
47	960	4,1	73	5,6	No break	First impulse did not cause rupture. Next two impulses consumed in stretching Swellex between top and bottom holder
47(a)	960	2,1	106	6,2	No break	
47(b)	960	3,1	155	6,2	No break	
47(c)	960	4,1	322	2,5 elongation	No break	

* Slip energy except where otherwise noted.

Design values : Rupture energy : 4,6kJ (mid-value between tests #46 and #47)

Elongation energy : 9,9kJ/100 mm (tests # 28, #38 and #48)

Slip energy : 5,8 to 3,0 kJ/100 (for embedded length of 1,4m,
from tests #24, #25 and #26).

- Notes:**
- i) **At 30 MPa inflation pressure, Swellex requires more than 1400mm embedment length in a long, straight hole to prevent sliding.**
 - ii) **In practice, slight dislocation and irregularities (such as dog earing) in the hole would prevent slip and the full rupture energy capacity of the Swellex tube (4,6kJ) would be utilized. Sharp dislocations in the hole might initiate a tearing failure at lower rupture strength, however.**
 - iii) **With sliding prevented and with a pressure-bonded contact length of 600mm in the ejectable portion, the welded ferrule at the collar of the Swellex failed at about one-half of the rupture capacity of the tube.**

The graphs of Figure B9 show that the combined slip and elongation responses to the repeated energy impulses were qualitatively very similar to that of the splitsets. Because of the lower-strength steel from which the Swellex tube is made, the rupture energy was considerably less than that of the splitset.

As with the other tendons tested dynamically, there was a considerable 'extra' amount of energy consumption that became available from Swellex tubes that were subjected to a 'first impulse' that was less than the critical value necessary to cause rupture. This was particularly evident in test No 47 where a total of 13,5 kJ, or more than 2,5 times the critical first impulse, was absorbed without failure occurring at the separation surface.

5 Discussion

Several interesting and important insights into the likely behaviour of support elements under real dynamic operating conditions were revealed by the practical difficulties experienced in the actual carrying out of the test programme.

After initial 'teething problems' centred around the difficulty of achieving sufficient stiffness for the test machine/test specimen interaction had been solved, unanticipated difficulties continued to be encountered. These were largely due to unrecognised 'weaknesses' in the terminal arrangements of the tendon elements as manufactured, which led to premature failure. These are effectively design inadequacies that should be urgently addressed by the manufacturers.

The creation of an accurately-dimensioned hole with the right kind of frictional properties into which to drive splitsets and inflate Swellex, also presented major difficulties. When a drilled 36mm diameter hole was finally achieved in strong, sharp 'synthetic rock' made of high strength, ultra-fine aggregate concrete, it proved almost impossible to hammer the split-set into the hole even with an accurately-guided pneumatic rockdrill. The heavy hollow bar specimen holder was firmly clamped to a very heavy work bench bolted to a concrete floor. Despite this, the total stiffness or solidity of the hole was clearly less than that of a hole in a solid rock mass. This probably contributed to the difficulty of installation of the splitset, perhaps through undetectable vibration losses in the energy transfer from the percussive blows of the rockdrill into the slender steel tube that forms the splitset friction rock stabilizer.

The more important of the insights which were gained largely from the difficulties rather than from the successful tests, are briefly discussed below:

- The very abrupt, even brittle, fracture of fully grouted, fully bonded steel bars which is often observed in a rockburst-damaged tunnel, was not easy to achieve under simulated conditions. This difficulty is attributed to 'softness' in the loading system. The fact that it took extreme measures to stiffen-up the supporting superstructure before it became possible to break a non-yielding tendon such as a rebar tends to support this view. The maximum stiffness attained for the testing system was probably still well below that of an intact rock mass.
- The practical implication of this 'softness' is that the theoretical deficiencies in energy absorption capabilities of stiff non-yielding tendons are not as evident as they might otherwise be in highly-deforming excavations in hard rock.
- Even very high strain rates do not overcome the 'protective' effect of the reduced stiffness of the loading system. In the real underground environment, this reduced stiffness results from factors such as:
 - i) the prior existence of significant fracturing in the tunnel walls;
 - ii) commencement of de-bonding by some earlier, possibly sub-critical, impulsive load;
 - iii) any 'softer' elements in the support system such as non-stiff plates, slack lacing, poor quality grout, incomplete grouting, etc.
- Where very strong jointed rock (in certain dykes for example) resists the development of a significantly softer shell of fracture around the tunnel, the stiff tendons will be more vulnerable to acute stress concentrations across the joint boundaries of large intact blocks

and abrupt failure will be more common. This enhanced tendency for brittle failure to occur has frequently been observed after rockbursts on a massive porphyry mine in South America, where static stress is insufficient to cause induced fracturing around the tunnels, and jointing is dominant.

- In uniform straight holes, hollow friction-dependent tendons such as splitsets (and to a lesser extent, Swellex bolts) will not break but will slide even if the hole diameter is so tight as to make the percussion insertion of the splitset very difficult. Obviously, if the hole diameter is less tight and installation is easy, the tendon will slide more easily. The possibility that operators will prefer less 'tight' situations and might even sometimes contrive easier installation, has to be kept in mind when split sets are advocated.
- The full potential tensile strength of friction-type tendons can only be utilised if the hole is just sufficiently distorted or dislocated to clamp the tendon without shearing it. However, guillotining and tearing of the steel tube is likely and conventional laboratory-determined strength testing is then irrelevant.
- Often it is inadequacies of the terminating arrangements on the tendons such as the welded ring on splitsets, the sealing weld and soft ferrule on Swellex, and the inadequate swaged sleeves on the loops of discard winding-rope strand, that fail prematurely and allow only partial utilisation of the potential strength or resistance of the tendon. These are shortcomings that require urgent attention by the manufacturers.

The repeatability and reliability that characterised most of the results for all of the various types of tendons that were tested were reflected by the consistency of the graphically presented data which, with only minor exceptions, showed smoothly varying trends and acceptably small scatter.

Where linear behaviour would be expected, the closeness of fit to a straight line was usually reassuringly good. Similarly, backward extrapolation of these curves usually came very close to passing through the origin of the graphs.

Probably the most striking and certainly the most significant effect that was consistently observed during the successful tests was the paradoxical tendency of tendons, subjected to a first impulse that was sub-critical, to acquire 'extra' capacity for absorbing more energy later if subjected to several more impulses. This extra energy was often considerably more in total than was necessary to cause failure at the first impulse, and it seemed to be evident in all types of tendons.

These additional amounts of consumed energy cannot be recognised or utilised in the strict application of a formal design procedure because the situation that permits the phenomenon is really one of conditional stability that cannot be predicted. The necessary condition that the first impulse should be less than critical for the paradox to present itself, probably occurs far more frequently than not. Taking into account the probability that quasi-static, dilatationary type sub-critical stretching induces the same effect, it is probably only very exceptionally the case that the first impulse will be greater than the critical value. Nevertheless, the un-enhanced rupture energy value is the only quantity that can be used as a design value in a rational design procedure. Naturally, it will lead to a somewhat conservative design, but not one which is unrealistic in any way.

6 Conclusions and recommendations

The development of a realistic and controllable method of testing support tendons dynamically, which has been achieved in this research project, offers a new and fresh opportunity for improving the design methodology for the support of excavations under rockburst conditions and, importantly, also provides an inducement for the development of innovative improvements in the support elements themselves and in their application.

As a result of this research project, a major step forward has been accomplished in that it is now possible to use the same rational procedure for the design of tunnel support as is classically employed for the design of structures or machine components in more rigorous and precise engineering disciplines - Ortlepp (1992: 594). Although the design values, which have been summarised in Table 1, are very approximate and have still to be validated against properly documented experience, they do provide a set of data where no data existed previously. Furthermore, the data were derived from simulated actual conditions and not from an idealised, laboratory situation.

It is considered very desirable, if not essential, to expand the knowledge in the field of dynamic phenomena in mine tunnels, in the following areas:

- check the performance of cone-bolts and any other rock-bolt types that purport to have a yielding capability, for example square twist bar.
- examine the effect of partial dislocation of the drill hole, particularly on the performance of the thin-walled steel tubes of the friction-based tendons, which results from limited shearing on joints or offsets on fractures in the surrounding rock mass;
- check on the desirability of prestressing cable anchors to relatively high values of pre-load

- find further confirmatory data for the beneficial or protective effects of the progressive debonding phenomenon.

With regard to the manufacturers of support items, the following challenges need to be met in both the area of existing responsibility and in future innovations:

- the elimination of weaknesses at the collar ends of splitset and Swellex bolts, and de-stranded hoist-rope tendons;
- the development of a simple, partial-locking end arrangement for smooth bars that will ensure their enhanced elongation response even when the effective embedment length is considerably less than the normal critical bond length.

W D ORTLEPP Pr Eng

T R STACEY Pr Eng

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8 Illustrations

- Figure 1. Damage in a deep goldmine tunnel after a severe rockburst.
- Figure 2. Test pieces of thick-walled tubing and 'rope-sling tendons.
- Figure 3. Twin-shell test pieces of 93mm O.D. showing method of damping.
- Figure 4. Test pieces containing splitsets and 18mm compact strand ropes.
- Figure 5. East end of swing-beam showing swivel-seat and anvil-collar damp below the beam jaw.
- Figure 6. General view of test facility.
- Figure 7. Diagrammatic sketch of test method.
- Figure 8. Reproduction of velocity recorder chart.
- Figure 9. Photograph of stiffened supporting structure.
- Figure 10. Close view of rupture of 16mm re-bar.
- Figure 11. Sliced section through test piece No. 6.
- Figure 12. Close-view of 'cup-and-cone', fractures in individual wires of 18mm diameter compact strand cable.
- Figure 13. Displacement during Tests 15 and 16 as a function of input energy.

APPENDIX A
TABULATED DETAILED RESULTS

APPENDIX B
GRAPHS OF TEST DATA

APPENDIX C

ESTIMATION OF SLIDING ENERGY AND ELONGATION ENERGY

APPENDIX D
RESEARCH PROPOSAL