

SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

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Final Project Report

Title: SUITABLE LONG TENDON TECHNOLOGIES AND PRACTICES

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EXECUTIVE SUMMARY

The use of tendons is the primary means of support in underground collieries. Therefore, in order to introduce safer and more effective tendon support systems, the performance of tendon reinforcement has been assessed.

In the main South African Collieries have relatively stable roofs compared to some of the other major coal mining countries. This is documented most clearly by the large cut-out distances that can be tolerated in many situations underground.

However, there are situations in most, if not all South African coal mines where long tendon support is necessary. Long tendon support systems currently in use in South Africa were reviewed and a number of shortcomings identified.

The objective of this project was to identify safer and more effective long tendon support systems suitable in South African coalmines. Appropriate test procedures for the evaluation of the performance of long tendon systems were also determined and are detailed in this report.

Long tendon systems currently in use in South African coal mines were reviewed and a number of shortcomings identified. Methods of improving the performance of these systems, bearing in mind the roof failure mechanisms identified in South African coal mines, are also suggested.

Internationally, a wide range of long tendon support types are in use. These systems were reviewed for their suitability for South African coal mine conditions and the selected system assessed through laboratory performance testing and compared with the existing South African cable anchor system.

Laboratory test results indicate that, in general, there are two long tendon reinforcement methods in use worldwide which offer improved performance over the cable anchor system currently used in South African collieries. These are the bulbed or birdcaged cable bolt system, installed in high strength grout and the flexible bolt system which adopts high strength capsule resins and small diameter boreholes.

Improvements can be made to the performance of the existing cable anchor system but this will involve changes to the current installation practice and/or to the design of the cable anchors themselves.

Underground field trials were established to compare existing and proposed systems in terms of ease of installation, quality control and system performance.

The system chosen for the underground trials was the flexible bolt, a stranded tendon installed like a rockbolt through capsule resin in small diameter boreholes.

Previous application of flexible bolts have shown system performance to be similar to fully encapsulated resin bonded rockbolts offering a high strength and high stiffness system.

Underground trials highlighted the benefits of the flexible bolts in terms of support installation and support effectiveness. Flexible bolts proved quicker and easier to install than existing cable anchors and provide better control over the installation quality. The flexible bolts are installed in smaller diameter holes than cable anchors, hence reducing drilling time, and, as they are installed in capsule resin, they can be installed during the normal drivage support cycle, hence speeding up drivage through dykes and difficult areas. Existing cable anchors have to be installed separately and slow down developments considerably. In addition, the flexible bolts provide improved support effectiveness as they provide a stiffer support reaction.

It was concluded that the adoption of the flexible bolt system in South African coal mines could result in a significant improvement in support safety and effectiveness.

Guidelines for the installation of flexible bolt systems and for improved quality control of existing systems were also drafted under this project.

1. INTRODUCTION

This is the final report for SIMRAC project No COL 704 entitled, "Suitable Long Tendon Technologies And Practices". The project was proposed to improve safety in coal mines.

In order to improve safety in South African coal mining operations it is essential that rock engineering and support practices be improved in the light of available international knowledge and best practice.

Considerable scientific advances in rock engineering, as applied to coal mines, have been made in recent years primarily as a consequence of research work undertaken in support of the introduction of rockbolting into UK coal mines. The improved knowledge relates mainly to the effect of rock stresses on coal mine roofs, and particularly to the mechanisms of rock failure and the performance characteristics of long tendons in maintaining roof stability.

In the main South African Collieries have relatively stable roofs compared to some of the other major coal mining countries. This is documented most clearly by the large cut-out distances that can be tolerated in many situations underground.

However, there are situations in most, if not all South African coal mines where long tendon support is necessary. Long tendon support systems currently in use in South Africa were reviewed and a number of shortcomings identified.

The objective of this project was to identify safer and more effective long tendon support systems for use in South African coal mines and to determine appropriate test procedures for the evaluation of the performance of such long tendon systems.

Internationally, a wide range of long tendon support types are in use. Under the COL704 project these systems were reviewed for their suitability for RSA coal mine conditions. The performance of existing and proposed systems were then assessed in laboratory performance tests and field trials.

The work programme aimed to provide outcomes that are used directly in the coal mines (and thereby provide a measurable safety dividend).

The primary outputs of this project are:

1. The introduction of safer and more effective long tendon support systems.
2. The development of an industry wide guidance documents for each long tendon support type to be used.
3. The identification of appropriate laboratory and field tests and monitoring methods to provide a measure of tendon performance and confirmation of roof stability.

The research programme involved the following stages:

1. Review of current RSA practice and guidelines relating to long tendon support and existing safety procedures, training notes, manuals and suppliers literature. Visit suppliers, rock engineers and a sample of mines.
2. Review long tendon support available internationally and determine relevant types for RSA coal mine roof failure mechanisms. Identify potential improved systems that address RSA coal mine roof failure mechanisms for performance testing.
3. Develop framework for testing and arrange field trials of proposed long tendon systems
4. Design, specify and carry out laboratory performance tests for existing and proposed tendon types.
5. Arrange for supply and develop framework to field trial new systems.
6. Undertake laboratory performance testing of long tendon systems to confirm performance criteria for guideline documentation
7. Carry out field tests to confirm performance of existing and new long tendon systems to confirm performance criteria for guideline documentation.
8. Discuss findings and agree new generic systems to be introduced with suppliers and rock engineers and mine management.
9. Draft Guidelines the selected long tendon type.

2. INITIAL REVIEW OF LONG TENDON SYSTEMS AND PRACTICE IN SOUTH AFRICAN COAL MINES

2.1 INTRODUCTION

This chapter aims to give a technical overview of cablebolt systems used in South African coal mines where approximately 25,000 are installed each year.

The cablebolt systems used are combined resin grout systems, based on plain single strand (7 wires), and usually have one or two 'bulbs' per cablebolt length, Figure 2.1. The bulbs are located at the top end of the cable to ensure proper mixing of the resin anchor. The cables are pre-tensioned and may be pre- or post grouted relative to this operation.

Mechanical anchor systems are also supplied but their application is less common in the coal sector than the resin anchor system.

2.2 SPECIFICATION

The current South African cable anchor system adopts resin point anchorage, which is normally pre-tensioned, and post grouted. The system is installed into holes drilled with either 36mm diameter or 38mm diameter drill bits and cable lengths range from 3m to 13m. Some small diameter cables are installed up to 3.5m long but these are not generally post grouted. The most commonly used cable lengths are 3.5m, 5m and 6m. Manufacturers / suppliers technical specifications indicate the resin point anchor cable anchor systems in common use in South Africa have ultimate tensile strengths ranging from 25 – 38 tonnes and working loads ranging from 16 to 25 tonnes for the 15.2mm and 18mm diameter systems.

Cables are bulbed only at the top, in the resin bonded section, and are plain unbulbed strand in the grouted section. Some cables are supplied with indents in the strand to improve the bond strength properties.

The cablebolts can be cut to length for site specific requirements. Resin capsule lengths and the number used will depend upon cablebolt length and resin anchor length. Two suppliers predominate and supply very similar products as detailed in the typical specification below:

Cablebolt Part	Specification
Strand Diameter	15.2 mm
Ultimate Strength	25-26 tonnes
Hole Size	36mm minimum, 38 mm nominal
Working/Pre-tension Load	16 tonnes
Resin Type	Fosroc Slow set 32mm diameter resin capsules
Grout Type	Typically CAPRAM
Dome Plate	150mm x 12mm with holes for grout tubes if post grouted,
Barrel and Wedge Anchor	Capable of being pre-tensioned, pre-tension anchor locking devices available

Details of the Barrel and Wedge Anchor Pre-Tension Locking Devices are as follows:-

- (i) 'Superlock' Anchor Locking Device Figure 2.2 (from Amalgamated Reinforcing)
A 'shear ring' is designed to activate at a specific load imparted by the hydraulic loading jack. The activation of the shear ring, in conjunction with a matching nose cone will effectively cause the wedge to lock off at a predetermined load. The displacement of the 'shear ring' is obvious and indicates that the anchor was pre-tensioned to the prescribed pre-load.
- (ii) 'DTI' Direct Tension Indicator, Figure 2.3 (from M & J Mining)
The gap in the middle of the barrel is precision machined and silicone inserted. When the anchor is fully loaded the gap will close and the white silicone will have squeezed out, thereby giving a visual indication of a correctly tensioned anchor.

2.3 INSTALLATION PROCEDURE

The cablebolts may be pre- or post grouted in relation to the pre-tensioning. The respective installation procedures are described below:

Post grouting

- (i) Resin capsules are pushed to the back of the hole.
- (ii) The 'anchor' is spun for the appropriate time and speed, as recommended by the resin manufacturer, at the same time as thrusting the cablebolt to the back of the

hole. The 'bulbs' ensure proper resin mixing while maintaining the cablebolt in the middle of the hole.

- (iii) A breather tube is fitted and cut to the same length as the cablebolt.
- (iv) A short filler tube, approximately 0.5m, is inserted into the hole and the hole is sealed off around the cablebolt, breather tube and filler tube. This is achieved by way of stuffing in material, hand packing of grout plinth or sponge packing.
- (v) The dome plate is placed in position, with the tubes and strand through the appropriate holes.
- (vi) The barrel and wedge are fitted over the strand.
- (vii) A 25 tonne stressing jack is fitted over the barrel and by way of a hydraulic pump, the system is pressurised until the barrel and wedge anchor device indicates the designated pre-load has been achieved.
- (viii) The jack is removed.
- (ix) The grout pump delivery tube is connected to the filler tube and grout is gradually pumped to fill the hole from the bottom. The hole is full when grout exits the breather tube. Both tubes are bent and tied off.

Pre-grouting

The above procedure is modified such that the system is pre-grouted prior to tensioning. Following (iv) grouting takes place and the tubes are bent and tied off. The dome plate (which does not need to have holes for the grouting tubes as this has been completed) is fitted as per (v). As from (vi) to (viii) the procedure is the same, pre-tensioning taking place before the grout has cured.

2.4. TYPICAL UNDERGROUND APPLICATIONS

There are two main applications in which cables are installed as additional support. These are in roadways driven in cross measures and in areas disturbed by structural features such as slips, and in particular within the perceived zone of influence of igneous intrusions i.e. dykes or sills. Figures 2.4 and 2.5 are photographs of South African cablebolts installed underground.

Reinforcement patterns vary, but typical installed lengths are between 3m and 6m Three or four cables are normally installed per row with rows spaced 1.5m to 3m apart.

Holes are normally dry drilled. In favourable circumstances, 10 or more cable installations can be completed per shift. However, hole drilling may be slowed considerably dependant upon the drilling conditions and the capacity and condition of the drilling equipment and services.

Bank Colliery, for example, is the largest user of cablebolts within Anglo Coal, installing approximately 350 per month. The mine operates a policy of installing cablebolts in all developments in cross measures and where slips occur which are common in close proximity to dykes.

In the 'SW1 Development' at Bank Colliery cablebolts were installed in heading roofs driven in cross measures, forming part of a three entry development. 15mm diameter 25 tonne strand was utilised with two bulbs for mixing the resin for the resin anchor. The cablebolts were 4.5m long and installed in a 36 mm diameter hole. Three 400mm long 32mm diameter resin capsules were inserted for mixing as the resin anchor. These were pre-tensioned to 15 tonnes and back grouted with thixotropic CAPRAM grout.

Typically 6 – 12 cablebolt holes can be drilled and installed per shift. These are spaced at 1.5 m along the roadway. In 5 m wide roadways there are typically 4 per row and where the roadways are 4m wide 3 will be used per row.

Guidelines for determining a requirement for cablebolting, and the pattern to be used vary between collieries and are generally unclear. There is no monitoring to indicate position and level of movement to confirm cablebolt length and reinforcement density. Some mines, for example, are currently revising Codes of Practice to give clearer guidelines on these aspects.

Quality control procedures covering installation are specified by the mines. These cover the use of approved materials and equipment, and lay down the installation procedures to be used, see example of SASOL guidelines in appendix 1. Commonly holes and cables may be inspected for length before grouting, and the breather tube for the presence of grout after grouting and before cropping.

Despite these precautions it is considered that poor installations are common. From the review of the existing cable anchor systems in use in South Africa a number of shortcomings, deviations and common problems were identified:-

- ? Most cable anchors are installed by contractors and common deviations include anchors not properly grouted or not grouted at all, cables cropped short when supervision is low, and, the level of pretension applied varies from site to site and from contractor to contractor. Common values quoted are 15 tonnes, 18 tonnes and 20 tonnes.
- ? Supervisors often have little expertise and generally possess a poor appreciation of the principles and mechanisms involved where cable anchors are applied. Adequate quality control is therefore not always enforced.
- ? There are no controls in place to check grout quality, i.e. the water to solids ratio is not monitored and the compressive strength of samples of grout from each batch mix are not checked.
- ? Non grouted cables are simply point anchored systems which do not address roof failure mechanisms involving rock shear failure, a common failure mechanism associated with most coal mine roofs in highly stressed areas.
- ? Few sites have written procedures for the correct installation of cable anchors and rely on the expertise and integrity of the contractors employed to install the systems. Contractors may not be fully conversant with best practice for cable anchor installations and are not operating to a generic standard.
- ? Cable anchors installed in the roadway sides and dipping to the back of the hole have been found to be installed with the breather tube installed to the back and the grout tube just through the mouth seal, similar to a roof installation. This gives rise to an air lock in the top of the hole and a grout return through the breather tube before the hole is fully grouted.
- ? The direction of lay of the strands in the cable anchors are supplied in both right hand lay and left hand lay. Where a right hand lay cable is spun in using a clock wise rotating drill machine and a left hand lay cable is spun in with an anticlockwise rotating drill machine there is a tendency for the strands to open during installation.
- ? Routine system checks involving load tests or pull tests are rarely carried out.

2.5. OPPORTUNITIES FOR ALTERNATIVE SYSTEMS

The two main defects of the existing systems and practice in use in South Africa are considered to be:

- a. System support effectiveness is likely to be low compared with alternatives available internationally.
- b. Installation is relatively complicated and laborious, requiring sub contract labour and resulting in variable installation quality.

RMT therefore consider that the introduction of improved long tendon reinforcement systems in South Africa would result in improved support safety and performance. An improved system would have some of the following attributes:

- (i) Holes able to be drilled quickly using existing hydraulic drilling machines or pneumatic leg drills.
- (ii) More effective at supporting the roof.
- (iii) Easy, and as far as possible, foolproof installation.
- (iv) Able to be installed by bolting crew rather than contractors.
- (v) Simple with a minimum number of components.

In the following chapters, work under this SIMRAC project to improve long tendon application in South African coal mines is described. Alternative systems are examined against the above criteria, and the selected system introduced and trialled in South Africa, working both with suppliers and mines.

3. INTERNATIONALLY AVAILABLE TECHNOLOGIES AND PRACTICE

3.1 INTRODUCTION

A wide range of different cablebolt systems are available and in use in hard rock and coal mines around the world, and current cable bolting practice in Europe, Australia, USA and Canada was reviewed for this project. However recent developments in high performance cablebolt systems and in techniques for the measurement of system performance have been concentrated in Europe and particularly in the UK, as a result of research part funded by the European Community. For this reason our review of current technology concentrates mainly on recent system development and testing work undertaken in the UK.

The birdcaged cablebolt, initially developed in Australia, has been used in UK coal mines in conjunction with rockbolts since the late 1980's, and it remains the de-facto standard against which new cable systems are assessed.

Development of alternative long tendon systems has, however, continued with the principal aims of speeding installation or providing immediate support, whilst maintaining the required reinforcement performance. Some of these systems are now proving equally successful and are being used as part of reinforcement systematically installed on drivage.

A laboratory short encapsulation pull test (LSEPT) has been developed in the UK for both rockbolt and tendon systems which measures bond strength and stiffness in rock and assesses the full range of potential failure modes. This test is now used along with conventional 'gun barrel' and shear tests to provide full assessment of bolt and tendon performance. This test is currently being incorporated into a new performance based British Standard for rockbolts and long tendon systems.

Rock Mechanics Technology Ltd has undertaken research into long tendon systems since the company's formation in 1994. The focus of the work has been the investigation of novel systems and concepts, as well as the development of laboratory techniques and underground testing and monitoring programmes for assessment of tendon performance. This work has been part funded by the European Coal and Steel Community, and latterly by The UK Health and Safety Executive.

This chapter reviews current international practice, and describes testing results using these new methods for the range of new tendon types available worldwide.

3.2 APPLICATION OF LONG TENDON REINFORCEMENT IN UK COAL MINES

Rockbolt reinforcement as roadway support was introduced to United Kingdom coal mines in the late 1980's. The level of reinforcement is determined by design based on in situ measurement (Altounyan P F R, Hurt KG 1998) and where this indicates that rockbolts alone are insufficient to maintain stability of the opening, long tendon reinforcement is also installed.

Initially, double birdcaged cablebolts were used as remedial reinforcement, in conjunction with cementitious grout, following Australian practice. A Code of Practice and British Standard governing their use were developed, and they proved outstandingly successful.

The birdcaged cablebolt was developed for use in stope reinforcement at Mount Isa, Australia, in 1983 (Kaiser and McCreath, A A Balkema, 1992). Application in coal mines soon followed, and by the late 1980's they were being used as remedial reinforcement in UK coal mines. The cablebolt is installed in predrilled holes up to 12m in length, and fully encapsulated with cementitious grout. Plain cable is replaced in this application, by unravelling and rewinding the strand to give an open weave cross section, which, when filled with grout, gives a greatly enhanced bond strength. Two cables are often combined in a single hole to produce the double birdcaged cablebolt (figure 3.1).

In the UK, single, or more usually double birdcaged cablebolts have been used as remedial reinforcement in conjunction with bolting systems since 1990. Kent et al, 1997, describes in detail the associated technology and design practices which are also covered by a Code of Practice prepared by the UK Mines Inspectorate (Deep Mines Coal Industry Advisory Committee, Health & Safety Executive 1996). In brief, the double birdcaged cable (DBC), consists of 14 wires from two 7-wire dyform strands conforming to BS 5896, and has a nominal UTS of 60 tonnes. The cables are birdcaged throughout their length. Specially formulated high strength grouts are used to fill the 55mm holes needed for the DBC. Single birdcaged cable bolts (UTS 30 tonnes) require a 43mm hole.

The success of these systems in the remedial support role comes from the combination of high bond strength and stiffness which maximises the reinforcing effect (Fabjanczyk M W , Tarrant G C, Nemcik 1992) and these parameters are of fundamental importance for long tendon performance.

The main disadvantages of the DBC system are the large hole required, which results in slow installation, together with the delay as the grout cures before the system is fully effective. There are circumstances in which early long tendon reinforcement is needed to control roadway deformation. Ideally this should be installed with the rockbolts as part of the primary support system at the face of the heading. However, birdcaged cables are unsuitable for this role.

The ideal long tendon reinforcement system should be as strong and stiff as a DBC, capable of rapid installation into small diameter holes and offering immediate support, making it suitable for use as primary support.

Active development of new systems in Britain has resulted in systems that come close to this ideal. The most significant innovation is the widespread use of full column resin bonded tendons (flexible bolts) up to 4m in length which can be installed with rockbolts as primary support. For remedial support applications smaller diameter grouted tendons are now used as an alternative to the DBC. Assessment of combined resin/grout bonded systems utilising pretension has also been undertaken. These developments and typical performance parameters are described below.

3.3 THE FLEXIBLE BOLT SYSTEM

The most significant and successful long tendon innovation in the UK since the introduction of the birdcaged cable has been the development of the 'flexible bolt'. These are steel cables of around 50 tonnes tensile strength and of similar diameter to a rockbolt, which are installed into polyester resin in exactly the same way. Although the use of cable in this way was not new, existing systems used plain cable, which resulted in poor bond strength and stiffness, and they could not be fully encapsulated at the lengths needed.

Profiling the cable by rolling a pattern of ribs/indents onto the outer wires was found to improve the bond strength, and two suppliers subsequently developed versions which exhibited bond strength and stiffness characteristics similar to the UK rockbolt system (Barratt D R 1997) (Figure 3.2). At the same time, the development of a super slow version of the polyester resin used, enabled flexible bolts to be fully encapsulated in lengths up to 5 metres. These developments have allowed flexible bolts to be used effectively as part of

systematic support patterns, in conditions requiring reinforcement beyond the bolted height and they are now in common use.

For most UK applications flexible bolts are used in combined patterns of rockbolts and flexible bolts with flexible bolts replacing some of the rock bolts in the nominal pattern. Figure 3.3 shows a typical example of a UK rockbolting pattern for a high deformation coal mine site adopting rockbolts only. In this case the level of reinforcement may ultimately have to be increased by adding cable bolts, as a backbye operation, in order to deal with further additional stresses imposed on the strata surrounding the roadway, particularly during longwall face retreat.

Figure 3.4 shows an alternative pattern of rockbolts and flexible bolts for the same roadway. In this case the need for additional cable bolts may be negated by the increased reinforcement capacity and reinforcement length provided by the flexible bolts. The rockbolts and the flexible bolts are installed at the face of the excavation during the development operation, thereby removing the need for a secondary support operation.

This approach has proved successful at a number of coal mine sites in the UK in removing the need for backbye cable bolting.

The UK HSE has recently issued guidance on the use of flexible bolts in UK coal mines (Deep Mines Coal Advisory Committee, Health and Safety Executive 2000) .

3.4 SMALLER DIAMETER REWOUND CABLES

Despite the success of the flexible bolt as part of systematic support systems installed on drivage, it is less suitable for remedial support of existing areas where significant roof deformation has occurred due to the limited length at which full encapsulation can be achieved and the risk of losing resin into existing fractures during installation. This means that there is still a role for grouted cables where remedial or longer support is required. A number of suppliers worldwide have introduced smaller diameter alternatives to the DBC for this role including nutcage, minicage, and bulbed cables. The smaller diameter needs a reduced hole size which in turn results in faster drilling and installation where this is a problem. Although the tensile strength of these cables is similar to the DBC the bond strength and stiffness is generally slightly lower due mainly to the configuration of the strand/grout system. To an extent this can be improved by increasing the cage frequency, and additional cables can be installed to give the same overall level of reinforcement.

3.5 COMBINED RESIN GROUT SYSTEMS AND PRETENSIONING

A number of long tendon systems are in use internationally in which short term support is effected using a polyester resin anchor with grouting undertaken to provide longer term reinforcement. These systems also usually make use of pretensioning. Systems currently in use in South Africa come into this category.

Systems examined have included a relatively highly engineered alternative to the DBC fabricated from steel rods and spacers and having built in grout ports as well as a resin anchorage and pretensioning facility, and more basic systems of the type commonly used in South Africa, in which plain cable is bulbed close to the upper end to mix resin capsules and provide an anchorage. The rest of the hole is then grouted after tensioning to a typical load of 10-20 tonnes. In some instances tensioned cable anchors are not part grouted and rely purely on the resin anchor to maintain the pretension load.

These systems have potential advantages in providing a reinforcement system which can be installed to the same length as the DBC, but provides immediate support as well as the long term security of grouted cables. However, at the present time, they generally use small diameter plain cable in the grouted length with large diameter holes and the poor resulting bond strength limits system performance. (see comparative test results in section 5).

Pretensioning is used with many reinforcement systems worldwide and a number of claims of its effectiveness have been made, sometimes accompanied by technical justifications of dubious validity. RMT have conducted studies into the effect of pretensioning using both laboratory testing and computer modelling. The main conclusion from this work has been that the principal benefit of pretensioning is to increase the effective stiffness of the tendon system to which it is applied. In practice pretensioned reinforcement systems exhibit infinite early stiffness, until the pretension load is overcome, when stiffness falls towards the unpretensioned value. (Figure 3.5)

A significant percentage of the cable systems used in Australia take advantage of pretension. Where these are applied, they are used in place of all forms of passive cable systems and in some cases as an alternative to standing supports. Although these are generally more expensive than conventional cable bolts (between 2 and 3 times more expensive in some cases) operators have found that in some applications these systems

can be installed to a lower density whilst maintaining support effectiveness, they give some indication that the cable is installed correctly if pretension load is achieved and they give immediate active support.

A wide range of products is available. These include highly engineered systems with deformed button or swaged ends offering load capacities of between 63 and 84 tonnes and, depending on resin type and hole size, pretension values ranging from 25 to 50 tonnes. Whilst post grouting of these highly engineered systems is relatively easy, lifting heavy tensioning jacks up to the roof can make the pretensioning operation arduous.

Other less expensive systems offer strand UTS values of 55 to 60 tonnes and, with barrel and wedge type end fittings, offer theoretical end load capacities of between 43 and 50 tonnes. These are generally pre-loaded to 20-25 tonnes. However, if overloaded, say through imposed ground stresses, the end fittings can fail catastrophically. These systems are post grouted in the same way that conventional non pretensioned cable bolts are, by adding breather and grout tubes separately before installation. Therefore, relatively large diameter holes are required to facilitate installation. Alternatively a range of cables similar to the flexible bolt are installed into resin in smaller diameter holes. These are partially encapsulated and pretensioned, or may be fully encapsulated as for the flexible bolt.

Pretensioning undoubtedly therefore improves the performance of low stiffness reinforcement systems, but this comes at a cost. Computer modelling demonstrates reduced confinement and therefore effective rock strength due to the pretension load at the top of the tendon anchoring section which could encourage rock failure at this position. The relative merits of this type of system, compared with an untensioned high bond strength/high stiffness system as exemplified by the DBC, are therefore unclear. Pretensioning implies a 'two stage' encapsulation process which complicates the system and installation process and increases the potential for operator error. A satisfactory installation then depends on the skills of the installation team. Subsequent loss of pretension load following installation due to slip, deformation or creep of system components or rock medium may occur in some circumstances, and this will adversely affect the support performance.

RMT are therefore encouraging suppliers to maximise overall system bond strength and stiffness for combined systems in both resin bonded and grouted zones, using optimum tendon geometry, even if pretensioning is intended.

3.6 DEVELOPMENT OF LABORATORY TESTING TECHNIQUES

The main means of assessment of long tendon reinforcement internationally is the use of axial loading of tendons installed in steel tubes, commonly referred to as 'gun barrel' tests. An example of this type, the double embedment test or DEPT (Figure 3.6), was adopted in the UK for assessing axial reinforcement performance. The system performance of reinforcement element/grout combinations is determined by analysis of load/displacement graphs with the displacement measured across the joint in the test assembly. This kind of test confirms the high bond strength and stiffness of DBC systems which results from birdcaging the strands. British Standard 7861, Part 2⁶ subsequently compiled for birdcaged cable systems used in coal mines, adopted this test and specifies a minimum bond strength of 560kN and stiffness between applied loads of 200 kN and 400 kN, exceeding 100kN/mm for DBCs.

The double embedment test measures system axial performance in idealised circumstances, but does not assess all potential failure modes and therefore forms the starting point for assessment testing. Figure 3.7 illustrates possible failure modes for a grouted tendon. Of these, only tendon failure in tension Figure 3.7(a), and shear failure through the grout or bond shear failure at the tendon/grout interface Figure 3.7(b), (i.e. tendon pulling out) are investigated by the DEPT. Shear failure at the hole wall (as shown in Figure 3.7(c) is deliberately suppressed by the internal thread present in the tubes, and in any case the use of steel tubes in place of a surrounding rock medium is a highly artificial substitute which may significantly alter the level of confinement generated under load and the resulting bond performance against other failure modes.

Shear failure of rockbolts and tendons due to roof shortening and shear under horizontal stress, as illustrated in Figure 3.7(d), is a known risk in high deformation coal mine roof and a shear test rig was therefore constructed at an early stage in the studies (Figure 3.8). This again utilises a tendon specimen installed in embedment tubes, which are then subject to shear movement. The shear strength of the system can be determined from the measured load. This double embedment shear test (DEST) is also incorporated in British Standard 7861 with a minimum shear force of 350kN specified for DBC's.

In order to more closely simulate the tendon system in its underground installed state it is necessary to include the rock/grout or rock/resin interface as part of the test arrangement. A laboratory short encapsulation pull test method, or LSEPT (Clifford and Kent 2000) originally

developed for rockbolts and based on a machine tool lathe was therefore adapted to enable tendons to be installed into sandstone and subsequently loaded axially. The apparatus, shown in figure 3.9, utilises 142mm rock core samples and simulates field installation procedures and features as follows:

- ? Control of revolution and feed rate of drill bit
- ? Controlled rate of insertion and spin of the tendon (for tendons installed in this way)
- ? Controlled confinement of the rock (for test samples up to 500mm long)
- ? Approximate simulation of semi infinite rock mass by steel outer cylinder (for tendon test sections exceeding 500mm)
- ? Laboratory level control of pull out test loads and displacement measurement

The initial test arrangement, used for rockbolts, made use of a biaxial cell to provide controlled confinement and to prevent rock sample tensile failure during testing.

This can be used for sample sizes up to 500mm in length. For tests requiring longer confined embedment lengths the use of a steel outer cylinder of the appropriate wall thickness to simulate the confining effect of a semi infinite rock medium proved successful in simulating actual modes of tendon system failure, including shear failure at the grout/rock boundary. In general core samples from a massive sandstone of 25MPa compressive strength have been used as the rock test medium, but tests have also been successfully undertaken in coal and mudstone samples. In the latter cases it has been found necessary to form samples from individual lumps bound together with weak grout.

The LSEPT is now used by RMT, in addition to the DEPT and DEST to fully assess the performance of long tendons. Bond strength and stiffness measured by this technique allows for the full range of potential failure modes, whereas the DEPT and the DEST measures maximum performance under idealised circumstances, with deliberate suppression of shear failure at the grout/rock interface.

The current British Standard (BS7861, Part 2) applies only to birdcaged cablebolt systems, although similar testing regimes have been applied to other long tendon systems. A review of the Standard is now taking place with the aim of broadening the scope to include newer tendon types and putting in place appropriate performance based requirements. It is likely that the LSEPT will be adopted as one of the performance tests used. This performance

based standard opens the door for further development of appropriate systems for use in British coal mines.

In addition to performance measurements, the LSEPT has been used in research to investigate aspects of the performance of tendons where information is currently limited or absent.

In addition to these specialist tests for measuring bond strength and stiffness, a range of conventional mechanical tests are also commonly applied to long tendons to measure the tensile strength of the tendon itself, and the strength of the end anchorage arrangement which commonly comprises a barrel and wedge anchor.

The latter test arrangement typically involves 'pull through' of the end assembly including any plate through a defined circular hole in a substantial bearing plate assembly. The diameter of the hole depends on the size at the end fixing, but is typically around 80mm.

3.7 TYPICAL TEST RESULTS FOR ROCKBOLTS AND LONG TENDONS

Double Embedment Tensile Tests

Figure 3.10 illustrates axial reinforcement performance of selected tendons as measured by the double embedment test. The high stiffness of the double birdcage cable in grout, up to its 60 tonne failure limit, is clearly demonstrated. The system is much stiffer than its plain cable equivalent. The figure also illustrates the high stiffness of the single birdcage cable in grout and UK AT rockbolt in resin, up to their respective tensile limits.

LSEPT tests for rockbolt systems

Use of this test allows comparison of bond performance of rockbolt systems in rock under realistic loading conditions. Figure 3.11 illustrates typical results for a range of systems including the AT rockbolt/resin system which is used in the UK and the flexibolt system in AT resin. The performance of the latter long tendon in AT resin is very similar to the AT rockbolt.

LSEPT tests for cablebolts

Using the same test method it is possible to compare various cable systems. Figure 3.12 illustrates the higher stiffness of the DBC compared with a smaller diameter bulbed cable, when compared using this test.

Figure 3.13 illustrates LSEPT results from investigations of the effect of roof strain on DBC systems prior to grout cure. These were conducted on a birdcaged cablebolt subject to a constant strain immediately following test installation, simulating installation into an actively deforming roof. The results showed that the cementitious cablebolt grout cured despite the continuous strain taking place. Cablebolts can, therefore, still be effective in actively straining roofs, albeit with a slightly reduced bond stiffness

The LSEPT has also been used to undertake research into the effects of pretension used with long tendon systems by installing test specimens up to 2.4 metres in length into drilled sandstone core within a steel confinement tube. Existing proprietary systems intended for pretensioning with a combined resin/grout anchor have been studied in this way. Figure 3.14 shows the results obtained from tests on an Australian pretensionable system and illustrates infinite stiffness up to the pretension load. The length of encapsulation resulted in high measured stiffness above the pretension load up to the tendon yield value.

3.8 CONCLUSIONS

The outstanding success of the grouted double birdcaged cable as remedial reinforcement results from the combination of high bond strength and stiffness which maximises the reinforcing effect, and these parameters are of fundamental importance for long tendon performance.

The main disadvantages of the DBC system are slow installation, together with the delay as the grout cures before the system is fully effective. Alternative tendon systems that overcome these disadvantages have therefore been developed.

The most significant and successful long tendon innovation since the introduction of the birdcaged cable has been the development of the 'flexible bolt'. These are profiled steel cables of around 50 tonnes tensile strength and of similar diameter to a rockbolt, which are

fully bonded using polyester resin cartridges in exactly the same way. These are now commonly used in lengths up to 5m as part of primary support systems.

Smaller diameter caged or bulbed cables have been introduced as alternatives to the DBC in the remedial support role. These can be installed more quickly because of the reduced hole size required, but they generally have lower bond stiffness.

The relative support performance offered by systems utilising a combined resin / grout anchorage and pretensioning, compared with an untensioned high bond strength/stiffness system as exemplified by the DBC, is uncertain, and they bring disadvantage in terms of more demanding installation procedures. RMT are encouraging suppliers to maximise overall system bond strength and stiffness in both resin bonded and grouted zones, using optimum tendon geometry, even if pretensioning is intended.

Recent developments in laboratory test methods have provided a means for assessing the performance of rockbolts and long tendon systems that more closely simulates the tendon system in its underground installed state such that the behaviour of the resin/rock or grout/rock boundary is included. The laboratory short encapsulation pull test method is currently used alongside previously adopted test methods, including the double embedment pull test (gun barrel test), the double embedment shear test and a range of conventional mechanical performance tests for tensile strength and end anchorage load capacity, to fully assess the performance of rockbolt and long tendon systems.

The LSEPT has also been found to be an ideal medium for research investigations into aspects of the performance of tendons for which information is currently limited or absent. A range of issues relating to pretension and the like have been investigated.

For the purpose of this project it is considered that the laboratory short encapsulation pull test method is the most suitable means for assessing the relative performance characteristics of existing and proposed systems. (See section 5 for details of test results obtained for South African cable anchors and for flexible bolts).

4. ROOF BEHAVIOUR AND APPROPRIATE SUPPORT SYSTEMS FOR RSA COAL MINES

4.1 INTRODUCTION

One of the key elements in the determination of appropriate reinforcement design is understanding the potential roof failure mechanisms which have to be addressed by the reinforcement.

The process required for obtaining such an understanding was rigorously explored during the development of the Advanced Technology Rockbolting system in the UK in the late 1980's and early 1990's. This process has since been applied in a number of South African coal mines, and is described below.

4.2 ADVANCED TECHNOLOGY ROCKBOLTING

Rockbolting has been successfully introduced in UK coal mines in recent years with unprecedented levels of safety (Arthur et al, 1998). The introduction of rockbolting was the result of a comprehensive research and development programme undertaken by British Coal prior to industry privatisation in 1994 and part funded by the European Coal and Steel Community. This work resulted in a fundamental advance in the science of rockbolting, which allowed its successful application in difficult conditions with large depths of working, weak rocks and interaction with previous workings.

Four key steps in applying rockbolting in these conditions were identified:

- 1: Understanding the roof failure mechanisms
- 2: Using a rockbolt system which provides effective support against these failure mechanisms
- 3: Designing the support pattern using in situ measurement
- 4: Monitoring the performance of the system

The resulting rockbolting system, together with the associated technology of design by measurement and routine monitoring of roof movement has been termed 'advanced technology (AT) rockbolting'(Bigby D 1997, Altounyan P and Hurt K G 1998). Development of the system followed identification of roof failure in UK mines as being primarily due to the action of horizontal stress.

Understanding stress, particularly the horizontal stress level, combined with the ability to undertake detailed measurement of stress by overcoring has been a key step in the successful introduction of rockbolting in deep coal mines (Cartwright P B 1997).

The significance of horizontal stress for mining stems from the concentration of this component which occurs in the roof and floor of mine openings (Figure 4.1a-f). If the resulting compressional forces exceed the rock strength in beds close to the opening then shear failure will occur, with lateral movement and vertical displacement of beds. Once failure is initiated, redistribution of load tends to cause progressive propagation of shear fractures higher into the roof. If these failures develop sufficiently or intersect planes of weakness such as bedding planes or slips, roof falls can occur.

AT rockbolting is a fully bonded high capacity and stiff rockbolt system designed to resist rock dilation and maintain rock strength under conditions of roof shear due to horizontal stress. Stiff systems such as this work by providing confinement to the rock, greatly increasing the effective rock strength, even in a post failure condition. Where long tendon support is required, strong, stiff systems are also used to maintain rock confinement.

This technology is used in all UK coal mines, and has been used in successful rockbolting trials at mines in Germany, Russia, Poland, Canada, the Ukraine, Sardinia, Japan and China. These were all mines in which rockbolting was being introduced in relatively challenging conditions, and in which horizontal roof shear was the primary failure mechanism, irrespective of the depth of working.

4.3 ROOF FAILURE MECHANISMS IN RSA COAL MINES

Understanding roof failure mechanisms starts with understanding the prevailing ground stresses and the properties of the rock strata surrounding the opening.

Prior to this project, investigations of in situ stress fields had been undertaken in RSA coal mines by RMT in order to investigate the appropriateness of the reinforcement designs being applied. Stress field measurements were taken in roof rock above the seam at several coal mine using the overcoring technique with CSIRO cells to ISRM standard procedures.

The stress measurement sites reflected a range of underground geological conditions.

A number of significant findings were made. Some stress measurements indicated the ratio between the maximum and minimum horizontal stress to be significant, in some cases greater than four, indicating the potential for significant directionality in the stress field. Measurements taken close to dykes (or other intrusive features) showed an increase in magnitude for both horizontal stress components compared with similar sites away from such features. Changes in both surface and underground topography were seen to influence stress levels, and some sites were found to suffer from higher average stress levels in combination with generally weaker roof.

Numerical modelling was used to assess the likely effects of these findings. Generalised computer modelling of coal mine roadways for South African coal mines using realistic material properties and measured stress levels indicated that the horizontal stress at some sites was sufficiently high on its own to cause shear failure of the roof. At sites close to dykes, failure is also feasible in combination with a slip feature.

Sites with generally weak roof in combination with elevated stresses were considered to be prone to roof failure due to horizontal stress effects.

The pattern of failure in all these cases was of lateral shearing movements and vertical displacement of the roof prior to a roof fall occurring, following the general pattern shown in Figure 4.1. Inspection of existing roof failure sites at a number of mines confirmed the characteristic signs of shear failure at all the sites seen.

The vast majority were associated with lateral compression of the roof strata induced by horizontal stress. In general two types of roof failure were observed :-

- ? Fall of roof strata between two converging shear planes.
- ? Roof falls associated with failure of the roof strata on one side of the roadway contacting a converging slip thereby forming a detached block. (Figure 4.2).

In both cases lateral movement of the roof, due to horizontal stress, was considered to be primary mechanism for roof failure. In the absence of this, the risk of falls would have been significantly reduced.

General experience in RSA already recognises that abnormal roof behaviour or difficult support conditions may be associated with structural features such as dykes, slips and seam undulations and zones close to these features are likely to be supported by long tendon reinforcement as well as rockbolts. Such areas have been identified as having elevated horizontal stresses and the reinforcement applied in these areas therefore needs to be effective in resisting roof shear and dilation.

4.4 APPLICATION OF EFFECTIVE ROOF SUPPORT SYSTEMS

Rockbolting systems typically used in RSA coal mines are point anchored with either mechanical anchor or partially or fully bonded, with a resin encapsulant annulus between the steel bolt and the rock.

Point anchored bolts have a low capacity and stiffness. The main role of such systems is in securing weak or friable immediate roof to stable upper beds (suspension) and they have little or no reinforcing action or resistance to roof shear under horizontal stress. The ability of fully bonded rockbolt systems to provide reinforcement depends on the strength and stiffness of the bond between the rockbolt and the rock. This can be measured in the laboratory or underground using short encapsulation pull testing (Deep Mines Coal Industry Advisory Committee, Health and Safety 1996) Figure 4.3. The performance of partially resin encapsulated types falls somewhere between these two extremes, depending on both the bond strength and degree of encapsulation.

The long tendon systems used in South Africa are relatively low capacity. Although they are stiff up to the pretension load if properly installed and pretensioned, if not they are likely to exhibit very low stiffness and strength. Also, should creep take place in the resin with time, under pretension load, such systems are in danger of unloading and becoming ineffective.

4.5 APPROPRIATE SYSTEMS FOR RSA CONDITIONS

Investigations at Goedehoop and elsewhere have confirmed that the principal roof failure mechanisms (lateral shearing due to horizontal stress) are similar to those in many other coalfields worldwide, and aspects of current world best practice, including the use of high strength, high stiffness bolting systems and design based on measurement (Arthur et al 1998), are therefore relevant.

The most effective bolting system to resist shear failure is one with high bond strength and stiffness. Short encapsulation pull testing of the bolting system in use confirmed that the existing system had low bond strength and stiffness. An improved rockbolt system with the required performance, and features allowing rapid installation and installation quality and performance audit, has been developed and is now in use.

The same principles identified for improved rockbolting systems are equally applicable to long tendon reinforcement.

The ideal long tendon system should have as many as possible of the following characteristics:

1. High capacity
2. Offer immediate support
3. High stiffness for maximum reinforcing effect
4. Fast installation on development for early reinforcement
5. Simple 'foolproof' installation

Judged against these criteria, existing RSA systems are likely to be far from ideal:

Although they do offer immediate support, they have relatively low capacity. Stiffness is high up to the pretension load if properly installed, but low beyond that and quality control of such systems is an issue. Installation is relatively slow and is an outbye operation using subcontract labour. Installation quality is dependant on the installers skill and defective installations are hard to identify once the installation is complete. There is no industry wide standard or generic means of quality control and therefore reliance is placed on the expertise and quality of the subcontractor used. With no regulation to control standards of workmanship of subcontractors for this operation the quality of cable anchor installations varies considerably.

The most appropriate alternative tendon system, currently available internationally is considered to be the flexible bolt.

The advantages of the flexible bolt system over the traditional cable anchor system are:

- 1) Flexible bolts are installed in resin with rockbolts at the face of the heading resulting in a high level of immediate support.
- 2) Flexible bolts are installed in small diameter holes thereby reducing the cost of drilling in terms of both drill bits and drilling times.
- 3) Flexible bolts are installed through capsule resin the same as conventional rockbolts, thereby simplifying the installation process and improving the quality control. They are easy to install correctly and difficult to install badly.
- 4) The flexible bolt / resin system offers a stiff system using standard resins.
- 5) Installation equipment and drilling consumables are the same as for conventional rockbolts and the bolts can be installed by the mines' heading teams, reducing the need for unregulated sub contract labour.
- 6) The installation of flexible bolts is much quicker than conventional cable anchors as there is no requirement for post grouting. Once the flexible bolt has been spun home and the resin has cured the installation is complete.
- 7) The system can be pre-tensioned the same as cable anchors and rockbolts by using two speed resins.
- 8) The system offers the mine significant savings by allowing more rapid drivage through difficult areas than by using cable anchors.

In addition, where reinforcement longer than 5m is required, flexible bolts can be installed as a combined resin/grout system and reinforcement length is then only restricted by drilling and installing equipment constraints. In France flexible bolts have been installed to lengths greater than 6m by installing the bolt through thixotropic grout and resin capsules pre installed in the hole, see Figure 4.4.

The flexible bolt was therefore selected for a laboratory assessment of performance and comparison with existing systems prior to a field trial.

4.6 SUMMARY

Two potentially improved systems have been identified which will address the roof failure mechanisms found in South African mine roofs. These are flexible bolts, installed in resin only or combined resin and thixotropic grout encapsulated flexible bolts and long tendon systems installed in grout, including birdcaged or similar cable bolts.

Flexible bolts with full resin encapsulation provide a strong, stiff system which offers a high degree of control over the installation quality of the cable. Flexible bolt systems in common use in the UK offer fully encapsulated tendons up to 5m long with ultimate strengths of up to 55 tonnes. The system can be installed in a standard roofbolt hole, thereby reducing drilling time and bit wear, and offers immediate support once installed.

The part resin part thixotropic grouted flexible bolt which can be installed with guaranteed full encapsulation to much greater lengths than 5m is commonly used in France. This system also offers high system stiffness with high strength and is again installed in relatively small diameter holes.

Control over installation quality with the flexible bolt is high, as polyester resin in capsule form is used and full encapsulation can be verified by observing excess resin at the hole mouth when installation is complete.

5. LABORATORY PERFORMANCE TESTING PROGRAMME

5.1 INTRODUCTION

In order to evaluate the performance of proposed long tendon systems prior to any field trial, laboratory pull tests (LSEPT and DEPT, section 3.6) were undertaken. Comparative tests were carried out on samples of the cable anchor system currently in widespread use in South African coal mines.

To assess the existing cable anchor system the laboratory short encapsulation pull test method (LSEPT) was adopted. Several tests were carried out to assess the full range of elements that combine to make up the system as shown in Figure 5.1 These are:-

1. Bulbed plain strand in resin in rock.
2. Unbulbed plain strand in resin in rock.
3. Unbulbed plain strand in grout in rock.

In addition to the tests on the current plain strand cable anchors, pull tests were carried out on notched strand cable anchors that are currently being considered by some mine operators as a potential improvement to the plain strand system. Tests include:-

4. Unbulbed notched strand in resin in rock.
5. Unbulbed notched strand in grout in rock.

The resin used with the cable anchors was Fosroc Fasloc 32/400 (Standard Fasloc resin) and the grout used was South African supplied cable anchor grout.

A range of tests were then carried out on the flexible bolt system, as supplied in the UK (with Exchem AT resin), Again the LSEPT method was used to provide a direct comparison with the cable anchor system results.

The test medium used for all of the laboratory short encapsulation pull tests was Hollington sandstone sourced in the UK. This is used because its properties under pull test conditions have been found to be similar to those of typical coal measures strata.

In addition to these tests, double embedment pull tests, were carried out on the flexible bolt system using a range of resin types. At the commencement of the project a preference was expressed to utilise locally supplied consumables where possible. It was therefore necessary to determine the effectiveness of the flexible bolt when used with South African supplied resins and to identify the most suitable product for the field trials. To determine this the double embedment test was used rather than the LSEPT method so that the only variable in the test was the resin itself. Therefore, idealised tests using steel embedment tubes and not rock cores was considered more appropriate. The resin types tested were:-

1. Exchem AT resin (currently supplied with the flexible bolt in the UK)
2. Fosroc Standard Fasloc
3. Fosroc Fasloc HS resin

The test procedures for the LSEPT and DEPT are detailed in appendices 2 and 3 respectively.

5.2 RESULTS FOR THE SOUTH AFRICAN CABLE ANCHOR SYSTEM

Figure 5.2 shows the short encapsulation pull test results for the South African cable anchor system including bulbed section, straight strand section (smooth and notched) in standard Fosroc Fasloc resin and the unbulbed sections of each strand installed in grout. These test results represent the relative performance of the various elements of the cable anchor when installed underground.

The tests were carried out as described in Appendix 2. The sandstone cores were drilled using standard Boart Longyear 36mm diameter full spade drill bits, as supplied to the South African mining industry for cable anchor installations and water flush was applied for hole debris clearance. The resulting core hole diameters were found to average 38mm diameter.

During testing a confining pressure of 10MPa was applied to the sandstone cores using the biaxial cell. Samples installed in resin were pull tested after 24 hours and samples cast in grout were pull tested after a 20 day grout cure period had elapsed.

In order to confirm test installation quality, the rock cores containing the tendon samples were split open and the samples inspected following the pull tests. This revealed that all

tests were good installations and the results are valid. Figures 5.3 to 5.7 include photographs of the split core samples.

The performance of the cable system is assessed by calculating the following :-

- 1) System Stiffness in load per unit displacement (kN/mm) between axial loads of 0-25kN, 25 – 50kN, 50-100kN and 100-200kN.
- 2) Yield Bond Strength (kN), defined as the axial load, when measured by pull testing, at which the system stiffness falls below a value of load per unit displacement of 20kN/mm.
- 3) Peak Bond Strength (kN)

Table 5.1 Average test results for Short Encapsulation Pull Tests on Cable Anchor System : 250mm Bond

Section Tested	System Stiffness (kN/mm)				Yield Bond Strength (kN)	Peak Bond Strength (kN)
	Loads 0 – 25kN	Loads 25-50kN	Loads 50-100kN	Loads 100-200kN		
Bulbed section in resin	67.5	7.5	9.5	17	19	170
Unbulbed smooth strand in resin	-	-	-	-	-	7.5
Unbulbed notched strand in resin	69	14	-	-	28.5	37.8
Unbulbed strand (notched and smooth) in grout	9	-	-	-	<8.5	8.5

The test results indicate that it is possible to generate significantly greater loads in the resin / bulbed section of the anchor than in any other part of the system. However, the bulbed cable section installed in resin represents a relatively short section of the bonded length of a completed cable anchor and was also found to give a very low bond strength and low system stiffness when compared to birdcaged cable bolts in grout or resin encapsulated

rockbolts. Figure 5.8 shows the comparison with test results for a standard AT rockbolt installed in AT resin.

The use of notched strand in resin was seen to improve both bond strength and system stiffness over the use of smooth strand (figure 5.9). However, this benefit was not evident in grout (figure 5.10) and the performance of the notched strand in resin was still relatively very poor when compared to rockbolts installed in resin. The notched strand did exhibit a relatively good system stiffness up to the yield bond strength of this element of the system and the yield bond strength was similar to the bulbed section in resin for the adopted bond length (Figure 5.9).

5.3 RESULTS FOR THE FLEXIBLE BOLT SYSTEM

Figure 5.11 shows the results of tests carried out using the LSEPT method to test the performance of the flexible bolt system as supplied in the UK, with Exchem AT resin.

Again, these tests were carried out as described in Appendix 2. The sandstone cores were drilled using standard UK drilling consumables comprising Firth Rixson 27mm diameter twin wing negative rake drill bits and hexagonal profile drill rods (19mm AF) with water flush for hole debris clearance. The resulting core hole diameters were found to average 28.5mm in diameter. During testing a confining pressure of 10MPa was applied to the sandstone cores using the biaxial cell.

Samples were pull tested 1 hour after installation and again core samples were split for inspection to ensure installation quality. Figures 5.12 to 5.14 include photographs of the split core samples.

The performance of the system is assessed using the same criteria used for the cable anchors. Table 5.2 below summarises the results.

Table 5.2 SHORT ENCAPSULATION PULL TEST RESULTS FOR FLEXIBLE BOLTS INSTALLED IN AT RESIN

Test No	System stiffness (kN/mm)				Yield bond strength (kN)	Peak bond strength
	loads 0-25kN	loads 25-50kN	loads 50-100kN	loads 100-200kN		
1	357	122	119	39	211	239
2	250	192	82	32	213	213
3	139	83	82	33	>211	211

The results were more consistent than the cable anchor results with all three tests showing similar results.

Comparison of the results shown in tables 5.1 and 5.2 indicates that the stiffness and bond strength characteristics of the flexible bolt system were considerably better than any of the elements of the cable anchor system in this test configuration. Figure 5.15 compares the best result from each reinforcement element test and relates this to the AT bolt/AT resin results shown earlier. This graph highlights that the flexible bolt system compares favourably with the AT bolt/AT resin system showing slightly lower system stiffness up to 160kN load but improved performance in terms of both stiffness and bond strength at loads greater than 160kN. The yield bond strength was determined as 213kN for the test result shown, compared with a yield bond strength achieved by the cable anchor system of 38kN, for unbulbed notched strand in resin, and 28kN for bulbed strand in resin.

These comparisons indicate the potential improvements available in reinforcement effectiveness throughout the reinforcement height due to the greater bond strength and stiffness characteristics available where flexible bolts are adopted.

5.4 COMPARISON OF RESIN TYPES - DOUBLE EMBEDMENT PULL TESTS

Figure 5.16 summarises the results obtained with a flexible bolt installed in embedment tubes in both Fasloc standard resin and Fasloc HS resin and tested by the double embedment pull test method. The results were also compared with DEPT results for the flexible bolt installed in AT resin. The results from the tests with the Fasloc standard resin were relatively poor, and the tests gave a low level of consistency compared with the Fasloc HS and AT resins.

The results indicate that the standard fasloc resin would not generate sufficient load transfer to utilise the full potential of the flexible bolt system. However, the HS resin gives results more similar to the flexible bolt when installed with AT resin, as used in the UK and Europe. The early stiffness of the system installed in Fasloc HS was found to be lower than when installed with AT resin. However, the HS resin allowed higher ultimate loads to be generated in the bolt.

The HS resin should allow the potential of the system to be utilised more effectively. Therefore, these tests confirm that flexible bolts installed in Fasloc HS resin should offer a significant improvement in reinforcement effectiveness for South African conditions and this system is considered suitable for underground trials.

5.5 IMPLICATIONS OF RESULTS OBTAINED

In summary, the results indicate that with the South African cable anchor system it is possible to generate significantly greater axial loads in the bulbed section of the anchor, when installed in resin, than for any other part of the anchor. However, the results also indicate that, compared with standard birdcaged cable bolts installed in grout or an AT rockbolt in AT resin, the bond strength and stiffness of the system was found to be relatively low. This can be related to the design of the bulbing and the compressive strength of the resin where the stiffness of the bulbed cable system relies to an extent on the compressive strength of the material inside the bulb. The UCS (Uniaxial Compressive Strength) of Fasloc 70:30 resin is approximately 29MPa whilst the UCS of a good quality cable bolt grout used in UK systems is in excess of 80MPa. The compressive strength of South African grout was not measured.

The performance of the non-bulbed section of the anchor system was found to be very poor when installed in either resin or grout. This can be related to the large hole size in comparison to the diameter of the cable. For reinforcement systems of this type to be effective it is desirable to minimize the annulus between the cable and the borehole wall and this is particularly critical in the case of resin encapsulated systems.

The results for the notched strand cable in resin were better than the smooth strand cable in resin, indicating there may be some benefit in terms of system performance in adopting the

notched strand. However, this benefit was not evident in grout and, due to the large annulus with the cable anchor system, the performance of the notched strand in resin was relatively poor when compared to rockbolts installed in resin.

When used in practice the cable anchors are installed with a longer resin bond length than that used in testing. This allows sufficient pre-yield load to be developed to enable pretension loads of between 15 and 20 tonnes (150kN – 200kN) to be applied. Therefore, in practice, provided the bond in this section does not yield or creep significantly and that the pretension applied is maintained, the test results indicate that the system depends mainly on the resin point anchorage, with little benefit seen from the unbulbed section of the system in terms of axial reinforcement. The grouted section will offer some resistance to lateral shear but will provide only a low strength low stiffness reinforcing should the resin point anchorage fail.

Should the resin point anchorage suffer from the effects of either creep or bond failure, the implications are that the cable anchor system would eventually lose its pretension load resulting in a relatively ineffective reinforcement system.

Flexible bolts installed in small diameter holes using high strength resin, give a much improved performance over the cable anchor system in terms of system stiffness, peak strength and yield bond strength.

As the systems intended application utilises full resin encapsulation, offering a strong stiff reinforcement throughout its length, and the system does not rely on the use of pretensioning it does not suffer the same potential disadvantages related to creep or debonding / unloading effects that cable anchor system does. The flexible bolt system, therefore, not only offers a stronger / stiffer form of reinforcement that is quicker and easier to install to a good standard, it is also more reliable as long term reinforcement.

5.6 POTENTIAL IMPROVEMENTS OF EXISTING CABLE ANCHOR SYSTEM

There are a number of ways in which the existing cable anchor system may be improved. A marginal improvement in system performance would be gained by adopting notched strand over smooth strand for the section of cable installed in resin.

However, significant improvements in system performance are possible by looking to the success of other systems. There are two long tendon reinforcement methods in use worldwide that offer improved performance over the cable anchor system. These are the bulbed or birdcaged cable bolt system, installed in high strength grout and the flexible bolt system which adopts high strength capsule resins in small diameter boreholes. The cable anchor system is a hybrid of these two successful systems and could be improved by adopting the principles used in both of these systems.

For example bulbed cables in grout, like the birdcaged cable bolt, offer better performance than either plain unbulbed strand in grout or bulbed strand in resin.

Where resin encapsulation is adopted, this has proved more successful where ribbed or notched profile reinforcement is applied, unbulbed and in small diameter holes giving a small resin annulus. Large diameter holes and large annuli do not offer a stiff reinforcement system when resin is used. Where grout is used its successful application relies to an extent on its compressive strength. Therefore, high strength grouts should be used and high levels of quality control applied to ensure high standards are achieved.

6. FIELD TRIALS

6.1 CHOICE OF SITE

The aim of the underground field trials was to compare the performance, installation and quality associated procedure and controls of the proposed system (flexible bolts) with the existing cable anchor system.

In addition, it was intended that some technology transfer should take place with training of RSA personnel.

Performance would be determined by monitoring roof deformation behaviour in areas of similar conditions where each system was installed.

It was considered that an ideal trial site would be a development section at a mine where more than one road was being developed through an area of poor conditions related to elevated stresses, eg dyke developments, so that one reinforcement system could be installed in one road and the alternative system installed in the adjacent road.

A number of potential coal mine sites were visited in the early stages of the project including:-

- Ingwe, Douglas Colliery
- Anglo Coal, Goedehoop Colliery
- Anglo Coal, Bank Colliery
- SASOL, Syferfontein

Syferfontein was selected as the most suitable site available at the time.

6.2 SYFERFONTEIN COLLIERY

Of the sites visited a SASOL STEENKOOL coal mine called Syferfontein was considered the most suitable. At the site there were three parallel roads being driven through a dyke area. Figure 6.1 shows the plan layout of the roads in relation to the dyke and Figure 6.2 shows a cross section through one of the proposed development roads.

From the cross section it can be seen that the dyke is inclined rather than vertical. From experience at the mine it was considered that the area after the dyke (under the shadow of the dyke) was most likely to require additional reinforcement. At that time it was planned to install 6m cable anchors together with the conventional rockbolt support, at 3 per row at row spacings of between 2m and 3m, depending on conditions.

It was agreed with the SASOL rock engineering department that one of the three roads could be supported with flexible bolts instead of cable anchors as part of a monitored trial and that these should be installed to similar length and density. It was also agreed that the trial zone should be not less than 20m long and preferably 30-40m in length. To achieve this it was estimated that 40 flexible bolts would be required and that 5m flexible bolts would be adopted. Experience from the UK was that with 4m flexible bolts full resin encapsulation could be achieved and with 5m bolts up to 90% full encapsulation had been achieved.

The aim was to utilise South African consumables where possible and so the flexible bolts were to be installed in resin supplied by FOSROC STRATABOLT.

At this time the laboratory test programme was underway to determine the suitability of South African resins for use with the flexible bolt system.

As the project progressed there were a number of significant delays in the progress of the Syferfontein development roads. These delays meant that site availability would be outside the planned programme for the SIMRAC project and so a number of 3 month long extensions were requested to accommodate the trial at this site. Eventually SASOL rock engineering suggested an alternative site that had by then become available at Twistdraai Colliery.

6.3 TWISTDRAAI CENTRAL COLLIERY

A visit was made to Twistdraai to assess its suitability for the flexible bolt trials. At the time of the visit a series of seven roads, in Section 71 in the 4 seam, were being developed through a dyke area. Figure 6.3 shows the location of section 71 and Figure 6.4 shows the layout of roads being developed through the dyke. Experience of developing through dykes at the mine was that in the Burnt Coal zones, either side of the dyke, roof conditions deteriorated significantly. The adopted support strategy was to hand over development through these areas to dyke development teams who installed cable anchors in conjunction

with rockbolts. This generally slowed development rates considerably compared with drivages away from dykes.

In addition to developing through the dyke area, the development roads were being driven out of seam (above the seam) to avoid problems experienced in road 6, the first driven road, where methane gas in the burnt coal area had given rise to coal/rock bursts, see figure 6.5.

Discussions with the mine management indicated that two of the seven roads, road 1 and road 2, would be driven last and could be made available to facilitate the SIMRAC project. The mine were interested in the potential that the flexible bolt system offered and were keen to assess it through the field trial. Based on this and the appropriateness of the site layout it was recommended to transfer the trial from Syferfontein to Twistdraai.

6.4 INITIAL INSTALLATION TRIALS

As a pre-cursor to the main field trials a series of installation trials were undertaken at Twistdraai. The purpose of these was to check systems compatibility and the following checks were made:-

1. Compatibility of drilling consumables with drill machine.
2. Drill arm single pass height to ensure flexible bolts could be installed through the resin in a single pass.
3. Hole size achieved using locally supplied drill bits.
4. Resin capsule size in relation to hole size.
5. Resin viscosity. If too viscous this could defeat bolt installation, depending on available machine thrust, when trying to achieve full encapsulation.

A number of problems were highlighted from the installation trials including:-

1. The time taken to drill a 5m long 28mm diameter hole to accommodate the flexible bolt was too long, in excess of an hour per hole. This was longer than it took to drill 38mm holes. The reason for this was found to be due to the design of the drilling consumables sourced in South Africa. The design of the drill bit and drill rods were not efficient at clearing drilling debris from the hole, resulting in clogging and jamming and hence reduced penetration. The short term solution was to import UK consumables for the trial.

Drilling trials subsequently carried out with the UK consumables gave average drilling times for a 5m long 28mm diameter hole of approximately 20 minutes per hole.

2. Problems were also encountered when inserting the flexible bolt through the resin capsules. In the UK a long single capsule of resin is normally used. However three capsules were using in this trial. The capsules were overlapping in the hole causing increased resistance to bolt insertion from the accumulated sheathing of the capsules. This was mainly due to the difference in the size of the capsules compared to the size of the holes, with small capsules, and a relatively large hole. To counter this problem resin capsules of slightly larger diameter were supplied. These were of 25mm diameter.
3. Further problems with bolt insertion, related to resin viscosity, were solved by reformulating the Fosroc resin to make it less viscous whilst retaining its strength/stiffness properties. Fosroc UK were in the process of developing a flexible bolt resin, for use in the European market. Details of the new resin formulation were sent from Fosroc UK to Fosroc Stratabolt in Johannesburg, and a more suitable Fasloc HS resin was then produced. However, full insertion of the bolt was still difficult. The final solution was a compromise whereby 3 capsules of resin instead of 4 were inserted giving approximately 80% total bolt encapsulation.

The original capsule specification of the resin for the flexible bolts was:-

1 x 500mm, 30 second fast set HS resin capsule inserted to the back of the hole, plus

3 x 750mm 10 minute slow set HS resin capsules inserted below fastest capsule.

This specification was designed to maximise the degree of resin encapsulation, giving almost full encapsulation of the flexible bolt, whilst facilitating single pass bolt insertion.

The change to the specification was as follows:-

3 x 750mm, 10 minute slow set HS resin capsules, only.

It was estimated that this new specification should enable at least 4m of the flexible bolt to be encapsulated in resin, (See figure 6.6)

The omission of the fast set resin simply meant that, during the trial, operators had to wait for the cure time of the slow set resin before dumping the machine drill arm. In practice with optimised consumables the fastset resin would be retained to speed up

installation. Once the problems with bolt installation were overcome the full trials were ready to commence.

6.5 MAIN FIELD TRIALS

6.5.1. REINFORCEMENT PATTERNS

Figure 6.7 shows the layout of flexible bolts and rockbolts installed in Road 1 in relation to the dyke. A total of 35 flexible bolts were installed, including one failed installation which was replaced by another flexible bolt immediately adjacent to it. Four rows of flexible bolts were installed before the dyke and six rows after the dyke. All flexible bolts were installed within 3m of the face of the excavation during drivage. The average width of Road 1 was 5.5m ranging from 5m to 6m in places. Also shown in figure 6.7 are the locations of the monitoring instruments, the tell tales and sonic roof extensometers.

Figure 6.8 shows the layout of the cable anchors and rockbolts installed in the trial zone in Road 2 in relation to the dyke. This road was developed first out of the two trial zone roads and cable anchors were installed as an outbye operation. When surveyed, there were five rows of cable anchors before the dyke and 13 rows after the dyke. Overall, this road was slightly narrower than Road 1 with its width averaging 4.5m to 5m. The positions of the monitoring instruments are also indicated in figure 6.8. Tell tales were installed during drivage but sonic extensometers were installed when roadway drivage was near completion and after the cable anchors were installed.

Figures 6.9 to 6.12 show a series of photographs from the two trial sites.

6.5.2. INSTALLATION EXPERIENCE AND TECHNOLOGY TRANSFER

Under the supervision of an RMT engineer the SASOL heading teams became relatively proficient at flexible bolt installation after each team installed only one or two bolts each. The system is quick and easy to apply, therefore was quickly learnt. Installation times, from the start of drilling to the completion of bolt installation ranged from 25 minutes to 40 minutes depending on drilling time and operator proficiency.

In the cable anchor supported roadway, the RMT engineers witnessed only hole drilling and cable grouting operations (on separate occasions) but not cable insertion. Hole drilling times were reported to range from 40 minutes to 90 minutes, depending on strata hardness. In general, cables are then batch inserted and batch grouted over the next two shifts (or next

two days where only one shift is worked per day). Therefore, completed cable anchor installations can take anything from 8 hours to 48 hours.

Full cable anchor efficiency is then only realised when the grout has cured fully. For cementitious products 28 days is generally recognised as the time required for the product to reach its full strength.

One of the objectives of the trial was to transfer the technology of correct flexible bolt installation to the South African mining industry. As well as written descriptions of the specification and installation procedures provided in this report, an RMT engineer undertook the training of underground development teams at the mine.

The aim was for SASOL to send a cross section of cable anchor teams to the site for training during the field trial and then subsequently for other mine operators to be invited to the site to witness the installations.

6.5.3. MONITORING RESULTS

Sonic Extensometers

Two sonic extensometers were installed in each trial zone. Their location was selected such that each extensometer was monitoring the same sequence of lithology as the corresponding extensometer in the adjacent road.

The main difference between the two trial zone extensometers is that those installed in the flexible bolt road were installed close to the face during development drivage whilst those installed in the cable anchor road were not installed until after drivage and cable anchor installation were completed. The implications of this are that the two extensometers installed in the cable anchor road will have missed any initial roof movement that may have occurred following excavation and are only useful for confirming subsequent stable conditions.

The extensometers installed in the flexible bolt road will indicate all roof movement that took place following excavation. Figures 6.13 and 6.14 show the results from the flexible bolt trial zone road (Road 1) and figures 6.15 and 6.16 show the results from the cable anchor road (Road 2). All four extensometers were installed to 7m into the roof.

Personnel from CSIR Mining Tek were responsible for installing and reading the extensometers for the project.

The extensometer results for the flexible bolt trial roadway which potentially record the complete roof movement from soon after excavation, (Figures 6.13 and 6.14) both indicate the development of small movements in the first metre of roof, approximately 2mm in the case of extensometer 1 and 4.5mm in the case of extensometer 2. There is no indication of significant movement above the first metre. In both cases the bulk of this movement had developed within one week of installation. Further readings, subsequent to those displayed, do not indicate any further roof movement.

The extensometers installed in roadway 2 (cable anchored section, Figures 6.15, 6.16) do not indicate any significant level of roof movement. The apparent negative movement shown in Figure 6.15 probably reflects disturbance of the base (target) anchor either during a subsequent reading, or due to slight shear in the immediate roof. However it should be remembered that these extensometers were installed well after excavation and therefore will have missed any early roof movement. The results agree with those in the flexible bolted area to the extent that they indicate stable roof conditions after any early roof movement has ceased.

Tell Tales

A number of tell tales were also installed in each road, see figures 6.7 and 6.8 for their locations.

The table below shows the tell tale readings observed during the final RMT site visit at the completion of the underground trials.

ROAD	TELL TALE (REF)	READINGS	TYPE
1	1	damaged	Rotary
	2	2mm	Rotary
	3	2mm	Plumb Bob
	4	1mm	Plumb Bob
2	1	4mm	Plumb Bob

It was reported that these tell tales were installed during drivage. The telltale in the cable anchor road was installed immediately adjacent to sonic extensometer No. 3 and indicates significantly more movement than the extensometer. This confirms that the extensometers installed late (after cable bolting was complete) may have missed initial roof movement.

The telltales in roadway 1 show levels of movement similar to those measured by the sonic extensometers and it can therefore be concluded that roof movement in the flexible bolted section over the period of the trial was around 2 – 4mm. The limited data available for the cable anchored section suggests that a similar level of roof movement may have occurred in each road.

6.6 TWISTDRAAI TRIAL SUMMARY

The trial installation of flexible bolts in road 1 of section 71 in 4 seam was successfully completed and the potential advantages of the system were demonstrated. Problems were overcome by sourcing improved drilling consumables and a larger diameter lower viscosity resin and reducing the encapsulation length to 4m. The flexible bolts were installed with rockbolts giving the maximum immediate support to the roof in the dyke area. The development teams found the installation of the flexible bolts to be quick and easy and became proficient at their installation in a short time. Control of installation quality was simply a matter of ensuring the correct quantity of resin was installed in each hole before inserting the flexible bolt.

The monitoring information obtained confirmed stable roof conditions with very low roof movement. Data from the cable anchored road was too limited to allow definite conclusion on comparative performance and further monitored trials would be appropriate to confirm the superior performance of flexible bolts.

7. THE INSTALLATION OF FLEXIBLE ROOFBOLTS – GUIDELINES

7.1 INTRODUCTION

Flexible roofbolts normally consist of a length of steel strand with one end fitted with a termination, such that the bolt can be engaged in a spinning tool located on a drill rig, and installed into a drilled hole by spinning and thrusting through encapsulated resin or grout. A flexible roofbolt therefore differs considerably from a cable bolt, in that its design allows installation by machine rather than by hand. The nature of the design also allows for various means of anchorage, for example:

- ? full column resin bonding
- ? full column grout bonding
- ? point anchoring using a resin capsule
- ? resin point anchored and post grouting using capsule or locally mixed grout

In all its forms, the requirement of a flexible roofbolt is to reinforce above the normal bolting horizon and, in order to achieve its design purpose it must be installed correctly.

The purpose of these guidelines is to provide information and guidance to enable the installation of flexible roofbolts to be carried out safely, and correctly.

7.2 DESCRIPTION

Flexible roofbolts are normally supplied in lengths ranging from 2 to 6m. As their main purpose is to act as a 'long reinforcing tendon' average length would be in the 5-6m range. The tendon itself consists of a group of high tensile steel wires wound normally in a clockwise direction. The tendon construction depends upon the supplier of the system. Commonly used systems are:

- ? a group of six equal diameter wires wound around a slightly larger king wire
- ? a group of nine small diameter wires wound around a core of six larger wires and a central king wire.

Diameter of the tendon is typically 22-23mm – similar in size to a rebar type bolt. This makes for a far less flexible strand than say a cable bolt, but allows for easy powered insertion through the grouting resin medium.

Typical ultimate tensile strength is around 55 tonnes, but, as the wires are drawn high tensile steel, elongation to failure is low – typically 6 per cent.

The upper end of the tendon (to be installed first) is normally fused to ensure easy penetration through the grouting medium, and to prevent unwinding of the strand during installation.

The lower end has a fitting which may be swaged or pultruded onto the strand. The pull-off strength of this fitting should match the tensile strength of the tendon. This fitting should also be capable of accepting a washer plate, the purpose of which is to provide some support to the immediate roof, and to have a load indicating feature. The end fitting also needs to accept a spinning adaptor for installation purposes.

7.3 INSTALLATION EQUIPMENT AND SITE PREPARATION

7.3.1 EQUIPMENT

Flexible bolts are designed to be installed using portable and chassis type drilling equipment. However, the flexibility inherent in the product makes it less suitable for portable equipment, and special care must be taken when using portable rigs.

Typical flexible bolt length is 4m. Typical hole diameters are:

- ? 27mm for resin bonding and thixotropic pre-grouting
- ? 35mm for post grouting

These relatively narrow hole sizes make for fast drilling times but require special drill strings. Drill rods with R17 rope-type integral couplings have been found to be most suitable for drilling 27mm diameter holes. R19 rope-type drill rods can be used for 35mm holes.

7.3.2 RESIN BONDING

It has been found that flexible bolts up to 4m in length can be satisfactorily fully bonded using encapsulated polyester resin. Typical capsule dimensions are 24mm diameter x 2000mm in length. This would provide sufficient resin for a 4m bolt. A single capsule is

preferable to allow both easier installation, and to ensure quality control. A curing time of around 5 minutes is desirable – again, to ensure ease of installation.

7.3.3 CEMENTITIOUS GROUTING

Several methods can be used to grout flexible bolts:

- ? Full column grouting using thixotropic materials

This requires the insertion of thixotropic grout via a tube or lance starting from the back of the hole and for at least half the hole length.

The bolt is spun through the grout to the back of the hole and held until set either via the machine or a restraining device.

- ? Point anchoring via a resin capsule

This is probably the most practical approach and involves locating a medium set resin capsule at the back of the hole followed by injection of thixotropic grout as above. The bolt is spun through both media and held at the back of the hole until the resin has set, thus offering an element of immediate support during grout curing.

- ? Point anchoring followed by post grouting

This requires drilling a larger diameter hole (say 35mm) followed by finishing off with a 27mm hole for location of a resin capsule at the top of the hole. Typical length of installation may be 6m. A device will be incorporated into the washer plate or similar to allow post grouting to take place following installation of the bolt by spinning into a resin capsule pre-installed at the top of the hole.

Prior to installation, check that all equipment and materials are located on site.

Test all drilling equipment to ensure correct operation. If pneumatic equipment is to be used, this should be in good condition, with system pressure at the nominal pressure required for the machine.

All drill rods, adaptors and bits should be checked for damage or wear, and replaced if necessary.

The drill string should be selected for the correct depth hole. If in doubt, this should be assembled and placed alongside a bolt to check compatibility.

The spinning adaptor should be checked for compatibility and condition.

7.4 INSTALLATION PROCEDURE

The required personal protection equipment – gloves, eye protection and ear defenders – should be worn.

The flexible bolts should be unbundled and laid flat along the ground. If coiled for transit great care should be taken in removal of ties and packing. Surface training is recommended prior to dealing with coiled bolts. Considerable strain energy is present in coils of flexible strand.

Check that the bolt is in good condition – free of kinks, deformations, and in particular that the upper end is fused, not partially unwound.

Assemble the end fitting (plates etc.) to the bolt.

Drill the correct depth hole. Ensure that the hole is clean by flushing or other standard practice.

Check that the hole is to the correct depth (not too short) by temporarily placing the bolt into the hole and ensuring that it can travel fully home.

For resin bonded bolts:

Install the correct amount of resin (typically half the hole length for a 27mm dia hole).

Manually insert the bolt into the hole and push up as far as possible. Mount the spinning adaptor in the machine chuck and engage on the end of the bolt. Carefully increase drill rotation bolt speed and feed the bolt steadily into the hole until fully home and spin for the specified time. Stop rotation but maintain drill thrust until the resin has cured sufficiently to hold the bolt in place. Finally tighten the nut/end assembly as specified.

7.5 PERFORMANCE CRITERIA

Assessment of the potential and actual reinforcement performance of flexible bolts can be undertaken by in situ measurement and this is the recommended approach.

Potential reinforcement performance can be measured by use of underground pull testing to determine the rock/resin/bolt bond shear strength. The method used for flexible bolts is detailed in HSE 2000 and reproduced in appendix 4. A pass criterion for acceptable bond strength for flexible bolts used in RSA needs to be determined on the basis of further research and field experience. Based on the laboratory test work reported here it is suggested that, as an interim measure, the same pass criterion as used in the UK is adopted. This is a bond strength of 130kN for a bond length of 300mm, averaged over a number of test horizons.

Actual performance needs to be determined by means of comparative monitored field trials using detailed extensometry (preferably sonic), following the general approach adopted for the field trial described in section 6. The use of telltales as visual safety devices is also recommended in areas perceived to be at risk from roof instability. Reduced roof movements and improved stability in flexible bolted sections compared with cable anchored sections in similar conditions would provide confirmation of the superior performance of flexible bolts.

8. CONCLUSIONS

8.1 The two main defects of existing cable anchor systems and practice in use in South Africa are considered to be:

- a. System support effectiveness is likely to be low compared with alternatives available internationally.
- b. Installation is relatively complicated and laborious, requiring sub contract labour and resulting in variable installation quality.

It is therefore considered that the introduction of improved long tendon reinforcement systems in South Africa would result in improved support safety and performance. An improved system would have some of the following attributes:

- (i) Holes able to be drilled quickly using existing hydraulic drilling machines or pneumatic leg drills.
- (ii) More effective at supporting the roof.
- (iii) Easy, and as far as possible, foolproof installation.
- (iv) Able to be installed by bolting crew rather than contractors.
- (v) Simple with a minimum number of components.

8.2 Based on these criteria the most appropriate alternative tendon system identified from international review was considered to be the flexible bolt. The advantages of the flexible bolt system over the traditional cable anchor system are:

- (ii) Flexible bolts are installed in resin with rockbolts at the face of the heading resulting in a high level of immediate support.
- (iii) Flexible bolts are installed in small diameter holes thereby reducing the cost of drilling in terms of both drill bits and drilling times.
- (iv) Flexible bolts are installed through capsule resin the same as conventional rockbolts, thereby simplifying the installation process and improving the quality control. They are easy to install correctly and difficult to install badly.
- (v) The flexible bolt / resin system offers a stiff system using standard resins.
- (vi) Installation equipment and drilling consumables are the same as for conventional rockbolts and the bolts can be installed by the mines' heading teams, reducing the need for unregulated sub contract labour.

- (vii) The installation of flexible bolts is much quicker than conventional cable anchors as there is no requirement for post grouting. Once the flexible bolt has been spun home and the resin has cured the installation is complete.
- (viii) The system can be pre-tensioned the same as cable anchors and rockbolts by using two speed resins.

The system offers the mine significant savings by allowing more rapid drivage through difficult areas than by using cable anchors.

8.3 Testing of alternative resins indicated that flexible bolts installed in Fasloc HS resin should offer a significant improvement in reinforcement effectiveness for South African conditions and this system was considered suitable for underground trials.

8.4 Recent developments in laboratory test methods have provided a means for assessing the performance of rockbolts and long tendon systems that more closely simulates the tendon system in its underground installed state such that the behaviour of the resin/rock or grout/rock boundary is included. The laboratory short encapsulation pull test method is currently used alongside previously adopted test methods, including the double embedment pull test (gun barrel test), the double embedment shear test and a range of conventional mechanical performance tests for tensile strength and end anchorage load capacity, to fully assess the performance of rockbolt and long tendon systems.

For the purpose of this project it was considered that the laboratory short encapsulation pull test method is the most suitable means for assessing the relative performance characteristics of existing and proposed systems. However, for full assessment of system characteristics the full range of test methods described in section 3 (the DEPT, DEST and LSEPT) are considered relevant for reinforcement system type testing of systems used in South Africa.

8.5 Laboratory testing indicated that flexible bolts installed in small diameter holes using high strength resin, give a much improved performance over the cable anchor system in terms of system stiffness, peak strength and yield bond strength.

As the systems intended application utilises full resin encapsulation, offering a strong stiff reinforcement throughout its length, and the system does not rely on the use of pretensioning it does not suffer the same potential disadvantages related to creep or

debonding / unloading effects that cable anchor system does. The flexible bolt system, therefore, not only offers a stronger / stiffer form of reinforcement that is quicker and easier to install to a good standard, it is also more reliable as long term reinforcement.

8.6 The trial installation of flexible bolts in road 1 of section 71 in 4 seam at Twistdraai was successfully completed and the potential advantages of the system demonstrated. Problems were overcome by sourcing improved drilling consumables and a larger diameter lower viscosity resin and reducing the encapsulation length to 4m. The flexible bolts were installed with rockbolts giving the maximum immediate support to the roof in the dyke area. The development teams found installation of the flexible bolts to be quick and easy requiring only a short training programme to become proficient at their safe and effective installation. Control of installation quality was simply a matter of ensuring the correct number of resin capsules were installed prior to bolt insertion.

The monitoring information obtained confirmed stable roof conditions with very low roof movement. Data from the cable anchored road was too limited to allow definite conclusion on comparative performance and further monitored trials would be appropriate to confirm the superior performance of flexible bolts.

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FIGURES

APPENDICES

APPENDIX 1

**Example of Cable Anchor Specification and Guidelines for Installation Provided by
SASOL Rock Engineering**

ROCK ENGINEERING DEPARTMENT
CABLE ANCHOR CONTRACT SPECIFICATIONS

For any contractor installing cable anchors at any Sasol Coal colliery, the following shall apply:

1. MATERIAL AND EQUIPMENT

- All materials and equipment be acquired from an approved supplier. This includes cable anchors and accessories, grout, temporary support, resin, tensioning equipment and drilling equipment.
- Should the contractor wish to use non-standard equipment, the Section Engineer must approve the use thereof.

2. INSTALLATION

- A joint agreement shall be reached by the responsible Mine Observer or Manager and the contractor regarding the initial making safe of the area where work shall be undertaken.
- Temporary support shall be installed at a spacing not exceeding that specified by the Rock Engineering Department guidelines.
- The contractor shall familiarise himself with the cable anchor installation procedure (Appendix A).
- The following breaches shall warrant non payment.
 - i) Cable cut short
 - ii) Anchor not tensioned to required pre-load.
 - iii) Hole grouted before cable length and hole depth has tails colour coded been verified and signed off.
 - iv) After grouting, the breather pipe found not to be filled with grout.
 - v) Breather tube and cable cropped prior to final inspection and signing off.

APPENDIX A – CABLE ANCHOR INSTALLATION PROCEDURE

1. Ensure that the correct material is on site.
2. Drill a 38mm hole, 0.5m shorter than the length of the anchor tendon.
3. Insert two 400mm x 32mm x 120 second resin capsules (marked “Cable Anchors” on the box) into the hole.
4. Insert the cable into the hole. Ensure that the cable is inserted to the very back of the hole – pushing it as far as possible before spinning the cable. At no time may the spinning time exceed the specified spinning time on the resin box.
5. Have hole depth and cable length verified.
6. Install plate, gasket, breather and delivery tubes – ensuring that the breather tube is inserted all the way to the back of the hole.
7. Tension the cable to at least 15 tonnes, taking care not to pinch or crimp the breather and delivery tubes in the process.
8. Grout hole with specified grout – until grout flows out at the base of the breather tube. Take care to make sure the breather tube is filled with grout – and to cement water.
9. Call for final inspection.
10. Cropping may only take place after written approval has been obtained from the mine’s designated supervisor.

CABLE ANCHOR INSTALLATION CHECKLIST / SIGN – OFF LIST

Mine _____ Section _____

Job details (eg panel name, road and split numbers): _____

Mine Observer: _____ Signature: _____

The appointed supervisor responsible for checking and signing off:

Name: _____ Signature: _____

Item	Date	Supervisor Signature
BEFORE WORK COMMENCES:		
1) Correct materials in place:		
38mm drill bits		
correct length anchors as specified		
correct “stonework” resin		
correct grout		
correct temporary support		
2) Work area made safe		
BEFORE GROUTING		
1) Hole depth correct		
2) Cable length in hole correct (ie not cropped at back)		
AFTER GROUTING		
1) Cable, breather tube, delivery tube, not cropped		
2) Breather tube, completely full of grout		
JOB COMPLETE AND ACCEPTABLE.		
Authorisation granted for cropping and payment.		

APPENDIX 2

TEST PROCEDURE FOR LABORATORY SHORT ENCAPSULATION PULL TEST METHOD

APPENDIX 2

The Laboratory Short Encapsulation Pull Test Method

The laboratory short encapsulation pull test procedure is used to determine bond strength and system stiffness. The laboratory short encapsulation pull test technique has been developed to test the tendon/grout/rock and/or the tendon/resin/rock system and is designed to simulate the underground installed condition of the tendon. The tests are undertaken using a lathe based test rig that enables an accurate simulation of the profile of the hole drilled in the rock to be achieved. The rock samples into which the hole is drilled in the laboratory has properties similar to coal measures sandstone and is sourced to give consistent samples for testing. These are batch checked using a standard control test. Once installed a hydraulic hollow jack is used to apply axial tensile load progressively until either bond failure or until 90% of the yield strength of the tendon is achieved. The end displacement and applied load are recorded.

Procedure – South African Cable Anchors

Sandstone core is placed in a biaxial stress cell and subjected to a confining pressure of 10MPa. A 250mm long hole is then drilled into the sandstone core using a 36mm diameter Bort Longyear twin wing bit applying water flush for hole debris clearance. A drill rotation speed similar to that used to drill roof holes underground is applied (440rpm). The hole is flushed clean to ensure no residual sandstone debris remains in the hole and the borehole dimensions are measured.

a) Bulbed and Unbulbed Section in Resin

To test the bulbed and unbulbed sections of the cable tendon in resin a short resin capsule of sufficient length to ensure 250mm encapsulation is then inserted into the hole. The bolt sample to be tested is placed in the lathe chuck & centralised and then the tendon is spun into the resin capsule mixing the resin during tendon installation, similar to the underground installation.

After a minimum period of 1 hour axial load is progressively applied to the tendon end by means of a hydraulic jack. The bolt displacement is measured at given load intervals.

b) Straight (unbulbed) Section in Grout

To test the unbulbed section of the cable anchor in grout the sample is turned through 90 degrees after drilling such that the open hole faces upwards. The cable tendon is placed into the hole by hand and centralised. Grout is mixed as per manufacturers recommendations then poured into the rock core hole until full. The tendon is agitated and rotated by hand to encourage grout penetration of the strand and to centralise the tendon inside the rock core. The assembly is then fastened to a fixing frame to ensure the tendon / grout / rock assembly remains centralised and undisturbed throughout its curing period. The sample is then left undisturbed for a minimum period of 14 days at a constant air temperature of 20°C.

After the appropriate cure period has been observed the pull test equipment is assembled over the tendon and double collets and wedges fixed to the tendon. Axial load is then progressively applied to the tendon in a controlled manner at a rate of 2kN/sec. Load development and axial displacement of the tendon are recorded throughout the test.

The performance of the cable system is assessed by calculating the following :-

- 1) System Stiffness in load per unit displacement (kN/mm) between axial loads of 0-25kN, 25 – 50kN, 50-100kN and 100-200kN.
- 2) Yield Bond Strength (kN), defined as the axial load, when measured by pull testing, at which the system stiffness falls below a value of load per unit displacement of 20kN/mm.
- 3) Peak Bond Strength (kN)

APPENDIX 3

TEST PROCEDURE FOR LABORATORY DOUBLE EMBEDMENT TENSILE PULL TEST METHOD

APPENDIX 3

THE DOUBLE EMBEDMENT PULL TEST

Determination of bond strength and system stiffness

1. Principle

The bond strength and system stiffness is determined from a double embedment pull test using slow set resin in conjunction with a length of rockbolt bar.

2. Apparatus

Use a test machine calibrated to BS 1610: Part 1, grade 1.0, having an autographic recording facility or other means of producing a load/extension graph.

The arrangement of the test assembly is shown in figure A 3.1 It consists of two thick-walled hollow steel tubes, of 50.5mm outside diameter and 27mm inside diameter. For steel rockbolts, the tubes are 125mm long and for grp rockbolts and stranded bolts and cables, the tubes are 450mm long. A 0.5mm deep by 2.0mm pitch thread is machined onto the internal surface of the tubes in order to provide a standard surface finish and hence to inhibit failure between this surface and the resin. Each of the outer ends of the tubes is to have an external thread which is compatible with the chuck adaptors.

Use a displacement transducer to record accurately the separation of the two tubes.

3. Procedure

3.1 Sample size

Three specimens are prepared using resin taken from the same mix.

3.2 Preparation of test specimens

Blank off the threaded end of one of the tubes and butt together the plain ends and secure the joint temporarily with adhesive tape. Fill the tube assembly with slow set resin which has been pre mixed in accordance with

the manufacturers' instructions. For a steel rockbolt test use a 250mm length bar and for GRP bolts, stranded bolts and cable bolts use a 900mm length tendon. Push the tendon bar into the resin by hand, whilst at the same time slowly rotating the bar and ensuring as far as is possible that the bar is centrally positioned within the tube assembly.

3.3 Curing

Allow the test samples to cure for at least 24h

3.4 Mounting

Fit chuck adaptors to the ends of the tubes and locate the test assembly in the test machine.

3.5 Loading

Apply a load to the test assembly in a controlled manner at a rate of $3\text{kN/s} \pm 1\text{kN/s}$ until such a time as the maximum load is achieved without further increase in load. Record the maximum load.

4. Results

Determine the bond strength and the system stiffness for the straight line portion of the load/extension graph from the mean of the three tests.

APPENDIX 4

UNDERGROUND SHORT ENCAPSULATION PULL TEST PROCEDURE FOR FLEXIBLE BOLTS

**EXTRACT FROM UK DEEP MINES COAL INDUSTRY ADVISORY COMMITTEES
GUIDELINES ON THE USE OF FLEXIBLE BOLTS TO SUPPORT
ROADWAYS IN COAL MINES**

UNDERGROUND DETERMINATION OF BOND STRENGTH FOR A STEEL FLEXIBLE BOLT/RESIN SYSTEM. SHORT ENCAPSULATION PULL TEST

Introduction

The short encapsulation pull test is used to measure the performance of a flexible bolt/resin/rock system. The test is performed underground and is the ultimate proof test of a flexible bolt/resin/rock system. It should replicate the procedures, consumables and equipment in use for the support.

Brief description

A series of holes are drilled to varying depths and flexible bolts of the required length are installed with a short resin capsule to give an encapsulated flexible bolt length of not more than 300 mm. The pull test needs to be performed after a curing period of at least 1 hour and not more than 24 hours. After this time an axial load is applied to the end of the flexible bolt and the flexible bolt extension measured. The load is applied up to a maximum of 220 kN.

Procedure

Equipment

The short encapsulation pull test equipment for flexible bolts is the same as for rockbolts.

Number of tests

A minimum of two tests need to be carried out at each of the chosen roof horizons. As an example, for a 4 m flexible bolt these horizons would normally be at 1200, 1800, 2600 and 3800 mm. If significant changes in geology occur within the bolted horizon, further tests need to be carried out at other horizons to determine their influence, if any, on the bond strength of any proposed flexible bolt reinforcement system.

Flexible bolt preparation

The flexible bolt length needs to be longer than the hole length to allow full engagement of the drawbar on the bottom end of the flexible bolt. All test bolts, including full length bolts, need to be cut square to the flexible bolt axis. The flexible bolt should be prepared to ensure that the resin is confined to the upper 300 mm of the flexible bolt to be tested. This can be achieved, for example, by using insulating tape wound around the flexible bolt, 300 mm from the top of the flexible bolt, to increase the effective diameter of the flexible bolt to that of the drilled hole.

Location

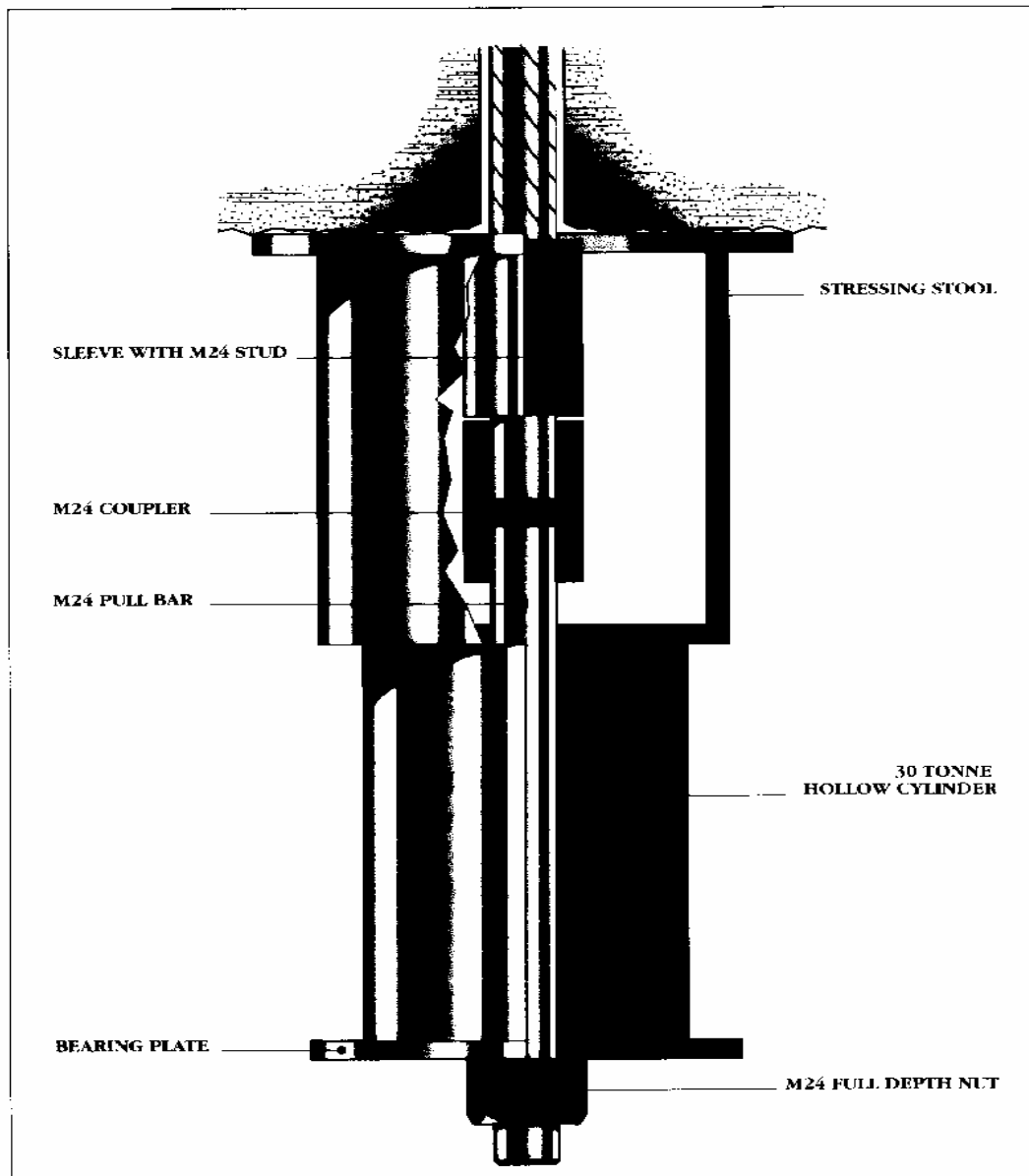
Pull test locations are the same as for rockbolts.

Capsule preparation and measurement of embedment length

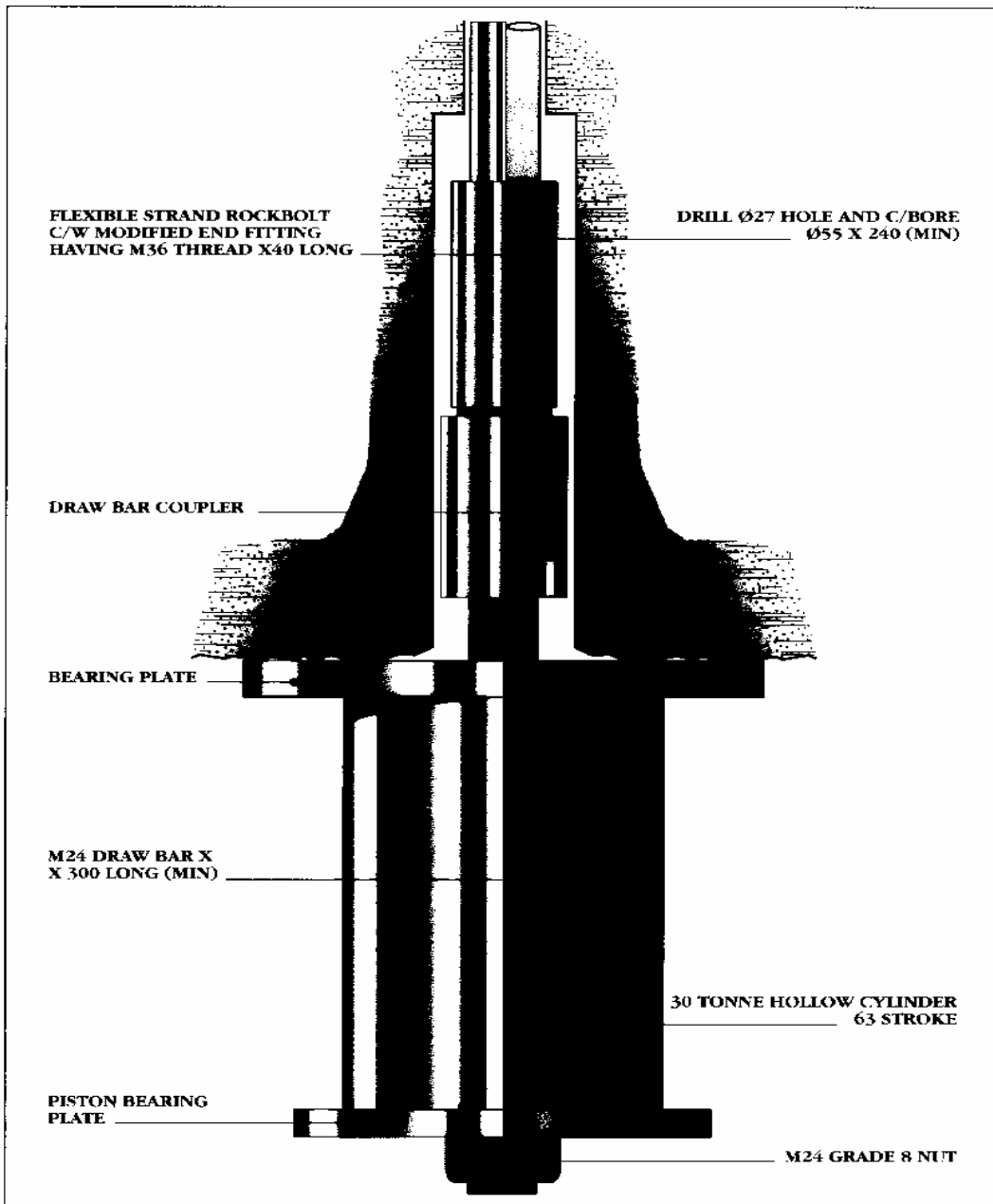
Method

- Drill hole to length using standard bit.
- Measure: drilled hole diameter; flexible bolt diameter; resin capsule diameter. Note - the flexible bolt diameter is the effective diameter as specified by the manufacturer.
- Determine the resin capsule length to produce not more than 300 mm flexible bolt encapsulation using the formula:

$$\text{Capsule length} = \frac{(\text{hole diam}^2 - \text{flexible bolt diam}^2) \times \text{encapsulated length}}{\text{Capsule diam}^2}$$



- Prepare test resin capsules of the calculated length from the resin used in the heading using the tie wraps and removing the excess capsule.



Hole preparation

Use the same procedure as outlined in the rockbolting guidance.

Flexible bolt installation

Follow the same procedure as outlined in the rockbolting guidance.

Pull testing

The procedure is substantially the same as that detailed in the rockbolting guidance using either set of equipment as detailed in Figures 1 and 2. Note that flexible bolt extension will depend upon an applied load, free length of bolt, and type of bolt. Flexible bolt extension is specific to the type of bolt used.

Analysis

Same procedure as for rockbolts to be followed.

Test requirements

The test requirements for flexible bolts are summarised below:

'The average bond strength should be no less than 130 kN, for a bond length of 300 mm, over 50% of the tested horizons.

Where the flexible bolts are to be longer than the rockbolts, at least one of the tests undertaken above the rockbolted height should produce a bond strength of at least 130 kN, for a bond length of 300 mm.'

Interpretation of results (for a 4 m length flexible bolt used in conjunction with 2.4 m length A.T. type rockbolts)

The following is text introduced to help with interpretation of results:

Example 1

Test	Horizon (mm)	Bond strength (kN)	Average bond strength (kN)
1	1200	120	$\frac{120 + 110}{2} = 115$
2	1200	110	
3	1800	150	$\frac{150 + 160}{2} = 155 \text{ (pass)}$
4	1800	160	
5	2600	150	$\frac{150 + 100}{2} = 125$
6	2600	100	
7	3800	170	$\frac{170 + 160}{2} = 165 \text{ (pass)}$
8	3800	160	

Two horizons out of four tested achieve a pass. This would satisfy the requirements of this guidance, as 50% of the horizons tested and at least one horizon above the rockbolted length have an average bond strength greater than 130 kN.

Example 2.

Test	Horizon (mm)	Bond strength (kN)	Average bond strength (kN)
1	1200	150	$\frac{150 + 100}{2} = 125$
2	1200	100	
3	1800	130	$\frac{130 + 110}{2} = 120$
4	1800	110	
5	2600	150	$\frac{150 + 160}{2} = 155 \text{ (pass)}$
6	2600	160	
7	3800	160	$\frac{160 + 90}{2} = 125$
8	3800	90	

Although five out of eight tests achieve a bond strength greater than 130 kN, only one horizon out of the four tested has an average bond strength greater than 130 kN. This would not meet the requirements of this guidance as only 25% of the tested horizons have an average bond strength of greater than 130 kN.