Performance tests for stranded ground reinforcement in mines

Prepared by
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for the Health and Safety Executive
Performance tests for stranded ground reinforcement in mines

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Stranded reinforcement tendons, flexible bolts up to 4m long and cablebolts up to 10m long, are becoming more commonly used in UK coal mines in conjunction with rockbolt reinforcement. At the outset of this project the reinforcement mechanisms mobilised by these stranded tendons were less well understood than those for conventional rockbolts.

The stability of a roadway will be compromised if the installed stranded tendon reinforcement fails and consequently it is important to have a method to determine in situ tendon integrity. A radio frequency technique was developed and applied which can clearly identify broken stranded tendons in coal mines with limestone roofs. It is anticipated, with instrument modifications, that this will work in coal mines with shaly roof strata. Instrumentation of stranded tendons prior to installation can provide another means of determining their integrity, for this the "Sentinel" flexible bolt was developed. More detailed information can be obtained using the newly developed strain-gauged flexible bolt. These advances in instrumentation of flexible bolts mean that the reinforcement behaviour and hence ground stability can be more accurately defined for up to 4m into the roof. These developments plus identification of improved instrumentation for ground deformation monitoring provide a basis for application to the longer cablebolts.

The Laboratory Short Encapsulation Pull Test was successfully modified for pull testing stranded tendons. This has provided valuable data and an improved understanding of reinforcement behaviour. Tests on a birdcaged cablebolt to simulate installation of a cablebolt into an actively deforming roof indicated that the grout effectively cured despite the continuous strain taking place. Pre-tension tests indicated that the stiffness of a stranded tendon system could be enhanced which could have advantages under certain load-deformation conditions in UK coal mines.

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EXECUTIVE SUMMARY

Stranded reinforcement tendons have become more commonly used in UK coal mines in conjunction with rockbolt reinforcement. These principally consist of flexible rockbolts used at the face of the heading to reinforce ground up to 4m into the roof and cablebolts used as remedial reinforcement up to 10 m into the roof.

At the outset of the project the reinforcement mechanisms mobilised by these stranded tendons were less well understood than those for conventional rockbolts. Through selected areas of research this project has been able to bring the measurement, testing and consequently the understanding of stranded tendon reinforcement significantly nearer to that of the conventional rockbolt.

If an installed stranded tendon fails the stability of the roadway will be compromised and consequently it is important to have a method to determine in situ tendon integrity such that additional reinforcement can be installed where necessary. Measurement of standing radio wave resonances was investigated and this was successful in both the laboratory and a limestone mine. A Patent Application for the orthogonal ground plane method has been granted and an application for the parallel tendon method is awaiting substantive examination. Despite success in the laboratory and a limestone mine, results in UK coal mines were disappointing. Refinements were investigated and excellent results were obtained from tendons in a French coal mine with a limestone roof. This work indicated that the resonant frequencies were very close to the frequency limits of the instrumentation and this could explain the poor results from UK coal mines with shaly roofs. Further work is expected to be able to address this.

Integrity testing of stranded tendons can also be achieved through pre-instrumentation of stranded tendons and these could be installed periodically within the pattern to check on the integrity of a sample of the installed cables in a roadway. Time Domain Reflectometry, TDR, was considered. This is based upon the principal of injecting an electrical pulse into a cable and observing the reflected echo. Although feasible, this method would have involved considerable practical difficulties and, as an alternative it was decided to develop an integrity method based on the system already being successfully used for rockbolts. A "sentinel" flexible bolt was successfully developed to monitor the integrity of a flexible bolt once installed. These have been successfully manufactured in 4m and 8m lengths.

Strain-gauging of a flexible bolt was successfully achieved through several prototype stages. Key problems were wire damage after fitting the end ferrule and torque nut and then further damage on installation with high torque hydraulic drilling rigs. The problems were solved by routing the wires through 2 diametrically opposite 'V' slots and using a barrel wedge for installation purposes.

A detailed knowledge of the rock deformation in the ground into which a stranded tendon is installed is fundamental in relating reinforcement strains to ground deformation for correct reinforcement design. An alternative to the sonic extensometer was investigated and several prototype alternatives tried. Within the time scale of the project it was not possible to develop a fully working prototype, but they all still represent potential alternatives for future investigations.
Within the UK, rockbolt/resin systems are tested in the laboratory with a short encapsulation pull test technique using a lathe and biaxial cell to confine the rock. This allows the system stiffness and bond strength to be determined under conditions that are much closer to those encountered underground. Under this project the test method was successfully adapted for testing grouted tendons. This included replacing the biaxial cell with appropriate steel split tubes and increasing the embedment length.

Tests were successfully conducted with standard birdcaged cablebolts installed in cementitious grout in rock. Further tests were undertaken to compare the performance of two other types of cablebolt. The test was successfully adapted to investigate how installation of cablebolts into an actively straining roof prior to grout cure may affect reinforcement performance. The results indicated that, despite the active straining, the bolt/grout/rock bond still effectively formed to generate good reinforcement performance. This equipment was also adapted to carry out pre-tension tests on a cablebolt system. These indicated that pre-tension may have significant advantages under certain conditions in UK coal mines.

Tests were conducted within coal rather than rock to simulate conditions in the coal rib. However the test results suggested that the steel confinement tubes generated more confinement than normally found in a coal mine rib. Tests in a particular type of plastic tube indicated that the particular type of plastic tube chosen provided too little confinement.

How a chosen reinforcement tendon behaves in-situ will in part depend up on the strata conditions in which it is installed. Good in-situ bond strengths are important for the success of a reinforcement design. This is a test parameter that cannot be fully simulated in the laboratory. Consequently an in-situ pull testing method was required for flexible bolts and cablebolts. A method was successfully developed for flexible bolts, modifying the method used for pull testing rock bolts. In-situ pull testing of cable bolts proved to be less straightforward and, to date, there is no satisfactory method available for such tests in the UK coal industry.

Due to the time scale of the project and the time taken to develop the instrumentation for measuring the integrity and load in stranded tendons, very few were installed. In the cases where they were installed they provided invaluable information, improving the understanding of the roof’s stability and confirming the suitability of the chosen design. Identification of suitable roof deformation monitoring instrumentation for heights greater than 7.5m combined with the success of the instrumentation of flexible bolts means that this project has made significant steps toward the adaptation of such systems for cablebolt reinforcement up to 10m into the roof.

Development of the laboratory test method for stranded tendons has provided a useful tool for assessing the reinforcement performance of different designs. The test allows the performance at novel types of stranded tendon reinforcement to be compared in conditions that closely simulate conditions underground. It also allows sensitivity studies to be carried out, such as the tests simulating actively straining roof and cablebolt pretension. However, it cannot totally replace in-situ testing to determine if the strata is suitable for reinforcement by a chosen system. In-situ flexible bolt pull tests are now successfully carried out to this end, but a method is still to be fully developed for cablebolts.
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1. INTRODUCTION

1.1 BACKGROUND

Ground reinforcement has been used increasingly as sole support for UK mine tunnels since the late 1980's. Until recently the reinforcement components placed close to the working face have been steel rockbolts. Where these fail to fully control ground deformation remedial reinforcement is placed, comprising long grouted cables with modified geometry to increase their efficiency. Being flexible, these cables can be considerably longer than the original rockbolts. They can therefore reinforce a greater volume and height of rock and can also act to suspend weaker strata from stronger strata above.

At the outset of this Project the reinforcement mechanisms mobilised by modified cables were poorly understood. Also, there were no means available for detecting whether these cables remained intact during their working life, other than the indirect method of monitoring the movement of the tunnel roof. Visual observation is insufficient as the cables are fully grouted and could be broken within the strata without any evidence at roof level. There was also no means available of assessing the loading condition of these cables in-situ. Solving these problems would significantly enhance the safety regime of rockbolted support for mine tunnels.

Several innovations had been introduced in the field of stranded ground reinforcement in mines. Firstly alternative designs of modified cable were being introduced. Secondly, flexible cables were developed which could be installed alongside or in-place of rockbolts at the face of the tunnel. These innovations further increased the requirement to understand the load transfer mechanisms utilised by stranded ground reinforcement and to develop means of measuring their integrity and state of loading in-situ.

1.2 RESEARCH AREAS AND OBJECTIVES

1.2.1 Integrity Testing

Rock Mechanics Technology Limited undertook a review of available in-situ reinforcement testing methods for the HSE [HSE, 1996]. The review identified low-frequency ultrasonics and radio-frequency resonance, RF, as methods which could potentially be applied to reinforcement already in place. The edevelopment of the ultrasonic method for use specifically on rockbolts was the subject of a separate proposal and has been reported under a separate project [HSE, 2000 (I)]. The RF method could, in principle, be used on stranded reinforcement as well as rockbolts.

Objective 1

Objective 1 was to investigate the feasibility of using the principle of RF resonance for determining the integrity of stranded ground reinforcements in-situ. It was anticipated that this would have included investigation of the possibility of avoiding any requirement for an installed ground plane and a study of the influence of roof mesh on any practical method.
Objective 1 has been addressed in Chapter 2.

1.2.2 Instrumentation for Integrity Measurement

In addition to the development of a method for integrity measurement of pre-installed tendons, other physical principles, requiring modifications or additions to the reinforcing element prior to installation, were also to be considered for application to the problem. These modifications were likely to involve the incorporation of electrical continuity circuits or strain measuring devices into the reinforcing elements. Three possible approaches were identified:

(i) TDR, Time Domain Reflectometry. This was an integrity technique identified for consideration under the review of available in-situ reinforcement testing methods for the HSE in 1996 [HSE, 1996].

(ii) An electrical continuity technique. It was considered that this could consist of a simple binary device, "on" or "off", which would indicate whether the reinforcement is intact or broken. It was also anticipated that the research could lead to a more sophisticated method based on a similar principle which could indicate the position of any break.

(iii) Strain measurement. Strain-gauged rockbolts were widely used to monitor and adjust the design of reinforcement systems. They provide a detailed strain-profile of the rockbolt under load using an array of typically 18 short strain-gauges. Strain-gauging of stranded tendons could therefore provide a similar level of information to aid the design of longer reinforcement systems. Strain-gauging of stranded reinforcements was considered to be feasible, although the problems of construction were likely to be considerable. Investigations were also conducted into alternative strain measuring techniques for standard and non-standard tendon which might survive strains up to tendon failure.

Objectives 2, 3 and 4 all related to the above instrumentation of stranded tendons for integrity measurement.

Objective 2
Investigate the feasibility and practical constraints on the use of TDR for testing the integrity of stranded ground reinforcement in-situ.

Objective 3
Investigate the principle of using simple electrical continuity testing methods to determine stranded ground reinforcement integrity. Possible methods of determining the location of any broken strands will also be explored.

Objective 4
Investigate alternative strain measuring principles for application to determining strain levels approaching failure for stranded and non-stranded ground reinforcement members.

These three objectives are addressed in Chapter 3.

1.2.3 Improved Deformation Measurement

The relationship between reinforcement strains and rock deformation is fundamental to the design of the support system. Although the "sonic" extensometer provides high
resolution data on rock deformation for typical 2.4 metre rockbolted systems, it is not long enough at 7.5 metres to monitor longer stranded reinforcement fully. The instrument’s flexible probe also suffers from a high capital cost and vulnerability to transport and handling damage. An alternative extensometry technique needed to be developed to overcome these flaws. One possibility was to use an inductive principle similar to that being developed for the remote-reading tell-tale system.

**Objective 5**
Investigate alternative extensometry principles that could be applied to overcome the current limitations of the “sonic” extensometer for precise measurement of the deformation of reinforced rock.

Objective 5 has been addressed in Chapter 4.

**1.2.4 Laboratory and In-situ Testing of Stranded Tendons**

Realistic testing of the complete reinforcement system, i.e. reinforcement, encapsulant and rock, in the laboratory and in-situ, is necessary for evaluation of the consumables involved and also to derive an improved understanding of the reinforcement mechanisms employed. This is particularly important in the case of stranded reinforcement, which is geometrically much more complex than a simple bolt. The existing laboratory testing procedures did not take account of rock-type, but simulated the drilled hole using a threaded steel tube. The use of rock specimens as host-material was proposed to investigate and eliminate this problem. In order to evaluate the integrity and load indicating principles discussed above, it was considered to be essential to test them to failure under controlled conditions in the laboratory. Furthermore no practical underground pull testing system for stranded reinforcement had yet been devised. This was required in order to evaluate system performance in-situ.

**Objective 6**
Develop laboratory and in-situ methods of testing complete tendon/encapsulant/rock systems in order to better simulate the reinforcement mechanisms mobilised by stranded ground reinforcement. A standard laboratory test will be devised which is suited for use in comparing the actual in-situ reinforcement capabilities of stranded reinforcement systems.

Objective 6 is addressed in Chapters 5 and 6 for laboratory and in-situ methods respectively.

**1.3 OVERALL PROJECT AIMS**

The aims of the Project were to improve the understanding of the reinforcement mechanisms mobilised by stranded ground reinforcement in mines, through improved load measurement, extensometry and testing, and to research suitable principles for measuring their in-situ integrity and performance.

The final objective, Objective 7, was therefore to apply the principles and methods described in section 1.2 to improve the fundamental understanding of the in-situ operation of stranded ground reinforcement.
Objective 7 is addressed in Chapter 7.

1.4 FUNDING

This project was part of a much larger project undertaken as part of an ECSC project which involved partners from France, Germany and Spain, [ECSC, 2000 (II)]. The ECSC project officially started in July 1997 and was due to be completed at the end of December 2000. This HSE sub-project commenced in July 1997 and was due for completion in September 2000. A three month extension until December 2000 was granted for writing up.

50% of the project costs were met by the 3.5 year ECSC project. The Health and Safety Executive contributed 30% towards RMT’s budget for the project. The remaining 20% of the funding was provided by the mine operators, consumable manufacturers and RMT itself.
2. INTEGRITY TESTING OF INSTALLED STRANDED TENDONS

2.1 INTRODUCTION

As stated in section 1.1 at the outset of the project there were no means available of detecting whether stranded tendons installed in UK coal mine roofs remain intact during their working life, other than the indirect method of monitoring the movement of the tunnel roof.

Rock Mechanics Technology Limited had undertaken a review of available in-situ reinforcement testing methods for the HSE under a previous project, [HSE, 1996]. The review identified low-frequency ultrasonics and radio-frequency resonance, RF, as methods which could potentially be applied to reinforcement already in place. The development of the ultrasonic method for use specifically on rockbolts has been the subject of a separate report [HSE, 2000 (I)]. The RF method was identified as a possible method which could, in principle, be used on stranded reinforcement. It was anticipated that considerable research and development effort would have been required to reach practical solutions.

Section 2.2 below discusses the extensive work carried out on the RF method.

2.2 RF - RADIO FREQUENCY

2.2.1 Principle of the RF Technique

The principle of the Radio Frequency, RF, technique is based on applying a radio frequency signal to a tendon in order to turn it into a radio-frequency antenna. This will have a fundamental radiating frequency which can be measured using an orthogonal ground plane, Figure 1. This radiating frequency will be dependant upon the length of the tendon and any change in the frequency will be indicative of a physical change in the state of the tendon such as failure. Since the results are dependant on tendon, rock mass and orthogonal ground plane type the system requires calibrating to determine the resonant frequency for a known tendon length at the test site with the chosen orthogonal ground plane.

2.2.2 Orthogonal versus Parallel Geometries

Initially, very promising results were obtained in the laboratory and in a limestone mine with an orthogonal ground plane.

Following the initial successful results a Patent Application for the method involving the use of a ground-plane reflector was applied for. This was subsequently granted, the GB Patent number being 2 304 417B.

Subsequent to the testing conducted with the orthogonal ground plane a complementary method was devised and tested. If the two terminals of the radio frequency generator were connected to an adjacent parallel reinforcement tendon then
strong resonances were observed at frequencies which were dependant up on the mean length of the two tendons.

This parallel geometry has potential advantages over the "orthogonal" arrangement:

(i) the resonant frequency of the orthogonal arrangement is a function of the ground-plane diameter as well as the tendon length. This means that the same size of ground-plane must always be used for comparative measurements, or a correction must be made,

(ii) the ground-plane has resonant frequencies of its own which, for short tendons in particular, could overlap and be confused with those of the tendon,

(iii) the parallel method avoids the necessity of carrying a ground-plane assembly underground.

A Patent Application for the parallel tendon method was applied for and is currently awaiting Substantive Examination. The UK patent application number is 9814455.3, publication number 2 339 286.

2.2.3 Initial RF Results

Despite the apparent advantages of the parallel ground plane method, results from underground UK coal mines with shaly roofs were still disappointing. Various measures were tried in order to improve the results. Impedance transformers designed to improve the performance of the method in coal-measures produced only limited success, even when combined with a new, more sensitive SWR meter. The resonances observed were generally "shallow", (confined to high SWR values), and "broad" in terms of frequency. Unlike the results in limestone, the coal-measure resonances were also dependent on connection geometry, i.e. which tendon was connected to the "earth" side of the instrument. This behaviour indicated leakage through the strata and/or over the tunnel surfaces. The geometry effect was practically eliminated by using a "balun" transformer, which is constructed so as to balance out the leakage currents as well as providing impedance matching. Even so, the best resonance obtained from a pair of 8 metre tendons in the roof of a Scottish coalmine was still shallow. This seemed to indicate that the impedance matching needed to be improved further. Alternatively, it was also considered that it may have been due to a high degree of RF loss (absorption) or leakage within the roof measures.

Measurements were also made on tendons in a Welsh slate cavern. Deep and distinct resonances were obtained in this medium without the use of matching devices, and the resonant frequencies corresponded with the two lengths of tendon known to have been installed during construction.

A standard technique for determining the lengths of feeder cables involves including a series resistor in the cable, so as to accentuate the changes in SWR as the frequency range is scanned. This technique was tried in the coal-measures at an early stage, with no detectable result, and was not found to be necessary in limestone or slate. Later laboratory tests indicated that a combination of in-line resistors with impedance-matching transformers and baluns may be helpful in reducing the minimum SWR for coal-measure resonances. Care is required, however, because the technique also reveals previously obscured resonances due to the transformer/balun and the connecting cables. These have been identified for a number of resistor/transformer combinations by laboratory measurements on tendon-pairs in different geometries.
Figure 2 shows the results from the limestone test mine, Scottish coal mine and the Welsh slate cavern. The results from tendons of known length show that the SWR frequency increases as the tendon length decreases. If a tendon was tested which was broken and consequently shorter the recorded frequency would be higher than expected.

A tendon with a physically short electrical discontinuity was installed in the limestone mine and successfully detected using the method, confirming that a broken tendon behaves in the same way as a short tendon.

It was not until a series of tests were undertaken at Meyreuil Mine in Provence that the most probable cause of the poor results in UK coal mines was highlighted.

2.2.4 RF Tests at Meyreuil Mine, France

The roof at Meyreuil coal mine consists mainly of limestone. The roof reinforcement system comprised a combination of 1.8m rock bolts, 4m flexible bolts and 5 and 7m birdcaged cable bolts, all fully encapsulated. Both the orthogonal and parallel method RF systems were tested.

Excellent results were obtained from the use of both the orthogonal and parallel test methods. A total of 4 broken nominally 4m flexible bolts were discovered, the breaks being at 1.4m, 1.4m, 2.0m and 2.4m, Figure 3. These tests showed that the resonant frequencies obtained for the longer cables in the French limestone were very close to the lower frequency limits of the instrumentation, probably due to the dielectric properties of the rock. It was therefore probable that the resonant frequencies in UK coal measures roof were below the current frequency range of the instrumentation. The instrument is currently being modified to extend its frequency range downwards.

It is expected that this work can be continued under a new ECSC Project to start later this year entitled “Improved Understanding of Reinforcement Behaviour”.

Under the current project, the RF system for stranded tendon integrity testing has been shown to be a practical tool for certain rock types (slate and limestone) and worthy of further development for shaly rock.
3. INSTRUMENTATION OF STRANDED TENDONS

3.1 INTRODUCTION

With the application of stranded tendon reinforcement systems for the support of roofs in the UK coal industry there is a growing need for monitoring their integrity and loading once installed into the roof (in-situ).

Under a previous HSE project, [HSE, 2000 (III)] work was carried out on development of an integrity monitoring rockbolt, known as the “Sentinel” bolt. The intact state of the rockbolt, which would be installed as part of the regular bolting pattern, can be checked periodically using a continuity meter. Under this project it was intended to develop an integrity monitoring flexible bolt. This would either use the “Sentinel” technology used for the rockbolt or TDR. Under a previous project [HSE, 1996] Time Domain Reflectometry, TDR, was identified as another possible method for determining the integrity of installed tendons. Section 3.2 discusses TDR for integrity monitoring and section 3.3 discusses the “Sentinel” principle.

Strain-gauged rockbolts have been used in UK coal mines since rockbolting was successfully introduced in the late 1980’s. With the introduction of flexible bolts over the last 4-5 years, which are being used increasingly as part of the standard bolting pattern, there is a need to understand the loads being developed by these tendons. Work under this project was directed toward developing a strain-gauged flexible bolt and this is described in section 3.4.

Investigations were also conducted into alternative strain measuring techniques for stranded and non-stranded tendons which might survive strains up to tendon failure (for rockbolts and flexible bolts the strains are recorded to the yield point of the steel). This is discussed in section 3.5.

3.2 TDR – TIME DOMAIN REFLECTOMETRY

This is a technique used in the electrical power industry, by computer networks and the telecommunications industry for locating faults in inaccessible cables.

The basic principal is to inject an electrical pulse into a cable and observe the reflected echo. Knowing the pulse velocity and by measuring the time for the reflected signal to return it is possible to calculate the position of the reflecting surface (fault).

The shape of the reflected pulse can also give information as to the type of fault, for example short or open circuit. Similarly, light pulses can be used for the same purpose using an optical transmission system and optical fibres.

In the case of tendon integrity testing it should be possible, by installing either electrical or optical fibres with the reinforcement tendons, to determine subsequent damage to the tendon.

The use of TDR methods for tendon integrity testing would require modifications to be carried out to the tendons prior to their installation under ground. As the “Sentinel”
rockbolt had already been developed it was decided to develop this integrity method instead as it presented a potentially much simpler and cheaper method of constructing a integrity monitored tendon.

3.3 “SENTINEL” FLEXIBLE BOLT

Prototype "Sentinel" flexible bolts were based on the 19 wire Exchem product, followed by application to the 7 wire Firth Rixson, (nee Arnall), product when this became the most commonly used version in the field. **Figure 4** shows these two types of flexible bolt which were instrumented. The “Sentinel” flexible bolt was developed through a number of prototype stages with extensive laboratory and field trials prior to development of the final product.

By unwinding an outer wire of the flexible bolt strand, an electrically conducting wire with an insulating sheath could be run along the flexible bolt within the interstitial space between the wires of the strand. This was electrically connected to the top end of the bolt. A jack-socket was mounted on the lower end of the flexible bolt with one of its contacts connected to the insulated wire and the other connected to the flexible bolt. Unlike the strain-gauged version of the flexible bolt, developed after the “Sentinel” flexible bolt and described in section 3.4, there was no apparent problem with damage to the electrically conducting wires when the flexible bolt end was subsequently crimped to fit the end arrangement used for bolt installation. In this case, with only one rather than many wires running through the interstitial space, there was still sufficient room for the wire after the crimping process.

When installed in the rock, the continuity of the resulting electrical circuit is an indication that the flexible bolt is still intact. Conversely, an open circuit indicates failure of the bolt. In order to distinguish between a genuine continuous circuit and a short-circuit fault in the wiring, a physically small resistor, 120 ohms, was inserted in the circuit at the top end of the flexible bolt. This has the added advantage that a strain meter, such as the Intrinsically Safe model used to measure strain-gauged bolts, may be used to monitor the “Sentinel” flexible bolt. The embedded wire, being copper, is more ductile than the flexible bolt steel, so that it will not fail in tension before the bolt, which would give a premature indication of bolt-failure. It was demonstrated in laboratory tests for failure not only in tension, but also in shear and bending, that in all cases the failure of the flexible bolt was coincident with the transition from continuous to open circuit.

The currently available version of the “Sentinel” flexible bolt has an additional sensing circuit connected to the bolt at its mid-point so that the approximate location of any breakage can be determined (within the immediate 1m or above). Failure in the upper half of the flexible bolt is sensed by one circuit; failure in the lower half is sensed by both circuits.

The design of the flexible bolt also allows the location of any breaks (within 100mm) post failure to be identified. This is based on measuring the change in capacitance along the bolt in the intact length below the break. The electrical conducting wire has a relatively high dielectric constant and is arranged in contact with the conducting surface of the flexible bolt. The disturbed capacitance between the flexible bolt and
the wire is monitored to detect any change in distributed capacitance value as a result of flexible bolt failure.

The 7 wire Arnall (Firth Rixson) product, 4.2 m in length, has been successfully installed and monitored underground in a number of UK coal mines. In addition an 8m long version of the “Sentinel” flexible bolt has also been produced for a client using their own type of stranded cable similar to the flexible bolt. These were for use in a metalliferous mine drivage to monitor the integrity of the installed cables during an extractive operation in the vicinity of the cable reinforced roadway which was expected to result in additional loading to the cable supports.

3.4 STRAIN-GAUGED FLEXIBLE BOLT

3.4.1 Laboratory Development of a Strain-Gauged Flexible Bolt

As for the “Sentinel” flexible bolt, initial prototypes of a strain-gauged flexible bolt were produced using the 19 wire Exchem product, FSR. Problems were encountered with passing the wires through the pre-crimped end of the bolt, Figure 4, and consequently the flexible bolts were sourced without the crimp for strain-gauging. However the wires were subsequently damaged when the flexible bolts were returned to the manufacturer for end installation. Several measures to try to overcome this problem were taken at which point the Firth Rixson flexible bolt, Reflex, became the product most used by the industry following its re-availability on the market. It was anticipated that the crimping of the end fixing onto a strain-gauged flexible bolt of this type would cause less problems as there were larger gaps between the wires of the Firth Rixson strands as shown in Figure 4. Several prototype strain-gauged versions of the Firth Rixson flexible bolt were designed and manufactured. However, as with the Exchem product, problems were encountered with the crimping of the end and also with fitting the torque nut damaging the wires. However a limited number of bolts withstood the process such that a significant number of gauges remained operational for installation trials.

3.4.2 Installation Trials of the Prototype Strain-Gauged Flexible Bolt

Initial installation trials using hydraulic bolting rigs in an underground coal mine highlighted problems as the high torque damaged the internal connections and wiring at the bolt end, this also tended to occur when lower torque pneumatic rigs were used. Two causes of the failures were identified:

(i) Torque relaxation
(ii) Crimp/Ferrule fitting

Torque Relaxation

It was demonstrated in static torque tests that a sudden relaxation or rapid variation in torque caused the outer wires of the flexible bolt to rotate temporarily relative to the central “king” wire. One possible relaxation mechanism, observed in the laboratory, was slippage of the torque-nut. This is positioned below the fixed ferrule and, because the anti-clockwise lay of the strand could slip away from the ferrule at high torque, the result of the transient rotation of the outer wires can be to crush or sever the strain-gauge connections. In order to eliminate this cause of failure, the strain-gauge connections were re-routed into two diametrically opposed “V” shaped slots in the king-wire.
The size and shape of the slot were chosen so as to minimise the reduction in cross-
section of the king-wire, whilst affording adequate mechanical protection for the bundle
of strain-gauge connections, particularly during the fitting of the end-ferrule and torque-
ut. Ferrules and nuts were fitted to short lengths of king-wire with different profile
slots ("U", "V" and rectangular) in order to assess the deformation due to the fitting
stresses. The "V" profile suffered the least distortion and a 12-gauge, 4 metre Reflex
unit was manufactured using a king-wire with two "V" slots, each 1.5 mm wide and
deep. Three of the twelve gauges had "earth faults" (connections to the tendon) after
fitting the ferrule and nut, but these did not affect the reading of the gauges. It had
been noted that fitting the torque nut involved considerable distortion to the short
section of tendon below the ferrule, which could have caused the earth faults.

Crimp (Ferrule) and Torque Nut
Fitting the ferrule and torque nut for installation involves considerable distortion to the
short section of tendon below the ferrule and was already acknowledged as a problem.
Following the investigations into the torque relaxation described above, a second unit
was manufactured and fitted with a ferrule, but no torque nut. This tendon had no
faults and was successfully installed in the roof of a limestone tunnel, using a modified
spinner coupled directly to the ferrule. No faults were generated on installation.

A third unit, fitted with two temperature compensation resistors in addition to the 12
gauges, was manufactured in the same way for installation in a coal-mine. However,
following fitting of the ferrule, several short-circuits were detected in the gauge
connections. Cross-sections of the ferrule were prepared and revealed localised
extrusion of the solid encapsulation from the slot, carrying some of the connecting
wires into contact with outer wires of the tendon, Figure 5. There were no electrical
faults outside the ferrule.

Two remedies for this problem were investigated. One was to modify the
encapsulation in the ferrule area so that extrusion did not occur when the ferrule was
fitted. The second was to replace the ferrule by a barrel-wedge. This was the
preferred solution to the problem.

The barrel wedge, Figure 6, is a standard alternative end fitting arrangement for the
flexible bolt and does not involve such high deformation of the tendon. A spinner was
designed which coupled to the barrel-wedge for installation and also provided
increased protection for the ends of the strain-gauge connections.

A flexible bolt of this design was successfully manufactured and installed in the roof of
a limestone tunnel. Figure 7(a) shows the flexible bolt with the spinner attached
shortly after installation. This is then removed for reading as seen in Figure 7(b).
Figure 8 shows the readings taken from this bolt. The loads and mean micro-strains
are all low as this is a shallow tunnel with a stable roof.

3.4.3 Results from a Strain-gauged Flexible Bolt Installed in a UK Coal Mine
The first strain-gauged flexible bolt installed in a UK coal mine roof was installed in
October 1999 at Welbeck Colliery in the Following Intake. It was 4m long and installed
into a deforming roof where additional remedial reinforcement had been required for
stabilisation. The results are shown in Figure 9. The instrumented king wire
exceeded its yield point of 30 tonnes above the rockbolted height. Significant bending movement was also indicated in this part of the roof at 3m. The results indicate that the flexible bolts in this area were providing a high level of reinforcement to the roof above the normal 2.4m rockbolted height.

Further strain-gauged flexible bolts have been manufactured and are available for commercial application.

3.5 HIGH STRAIN MEASUREMENT SYSTEMS

Investigations were also conducted into alternative strain measuring techniques for stranded and non-stranded tendons which could survive strains up to tendon failure (for rockbolts and flexible bolts the strains are recorded to the yield point of the steel).

Investigations were made into the use of extended strain-gauges in conventional (rigid) rockbolts. Replacing the copper continuity-wire of a "Integrity" bolt with a strain-gauge wire would indicate the increasing overall strain as the bolt approached failure. Several resistance wires connected to different points along the bolt to form "bays" could identify high-strain sectors along the length of the bolt. However, because of the averaging effect of such an extended strain-gauge, the interpretation of readings would depend on the assumed strain-distribution (both axial and lateral) within the bolt.

In order to quantify these effects, and to establish the practicality of a "strain-bay" bolt, standard slotted bolts were fitted with both conventional foil strain-gauges and single-wire extended strain-gauges. The test-bolts were subjected to shear, direct tensile and double-encapsulated tensile tests, and the responses of the two types of gauge compared.

For direct tensile conditions, an extended gauge recorded a maximum strain-change of 60,000 microstrain (6%) at failure. This is a greater range than is normally observed for conventional foil gauges, but less than the failure strain of the copper wire used in "Integrity" bolts. A second tensile test-piece confirmed the range limit.

Double-embedment shear and tensile tests were made on two test-bolts fitted with both conventional and strain-bay gauges. In the tensile test, the maximum bay-strain was 8000 microstrain compared with 40,000 microstrain for the two foil gauges, 50 mm away on either side of the break-line, and 3000 microstrain for the next-nearest gauges, 150 mm away. The shear test gave a maximum bay-strain of 630 microstrain compared with -1750 and 1130 microstrain for the nearest foil gauges to the joint, and 200 and 10 microstrain respectively for the next-nearest. Figure 10 shows the results obtained from the tensile and shear tests.

Thus, even for localised failures such as encapsulated shear, the extended strain-bay can give a measurable indication of failure which is of the same order as that recorded by discrete gauges at the standard spacing of 250 mm. Because the actual mode of failure can range from pure shear to pure tension, the output of a strain-bay bolt cannot be used to predict time-to-failure. However, the overall strain at which failure of the gauge occurs can be used to determine the mode of that failure. The rate of increase in overall strain could also be useful as an indicator of the relative stability of a number of strain-bay bolts.
4. IMPROVED DEFORMATION MEASUREMENT

4.1 INTRODUCTION

The relationship between reinforcement strains and rock deformation is fundamental to the design of the support system. Although the sonic extensometer continues to provide high resolution data on rock deformation for typical 2.4 metre rockbolted systems, it is not long enough at 7.5 metres to monitor adequately longer stranded reinforcement. The instrument’s flexible probe also suffers from a high capital cost and vulnerability to transport and handling damage. An alternative extensometry technique needed to be developed to overcome these flaws.

In section 4.2 the three types of alternative extensometer are discussed:

(i) Inductive Sensor Extensometer, section 4.2.1
(ii) Hall Effect Probe, section 4.2.2
(iii) Resistance Wire Extensometer, section 4.2.3.

4.2 ALTERNATIVES EXTENSOMETER TYPES

4.2.1 Inductive Sensor Extensometer

The prototype inductive extensometer uses the same measurement and addressing technique as used by the remote reading tell tale system developed under a previous HSE project, [HSE, 2000 (III)]. In this system a transponder measures the displacements using the principal of changing inductance of a coil as a ferrite rod moves through it.

Within the inductive sensor extensometer a series of transponders can be anchored at even spacings up an underground borehole. Considerable effort was devoted to development of a special anchor system to hold each transducer within the borehole. This employed a spring loaded system which was activated by releasing a shear pin once the transducer and anchor had reached the desired height into the borehole. Consecutive transducers would be fed up the hole and their anchor systems released. At the time each transducer is inserted up the hole it is ‘daisy chained’ together along a roadway. A readout interrogation unit could then be used to periodically measure the relative movement of the anchors with respect to a base reading to detect ground deformation in the same way as the sonic extensometer. The number of anchors and transponders will depend on hole length and the desired spacings between each. Unlike the sonic extensometer which is restricted to 7.5m this inductive sensor extensometer can be installed to much greater heights into the roof, easily coping with the 10 or 12 metres heights to which birdcaged cablebolts are installed.

A prototype inductive-sensor extensometer was manufactured for underground installation following laboratory trials. However this prototype was destroyed during installation, due to premature engagement of the spring loaded anchor-system of the first transducer. It was concluded that the spring loaded anchor system needed modification in order to prevent premature release.
This system remains the most feasible alternative to the sonic extensometer, as most of the technology is already tried and tested, such as the transducers and IS interrogation units. Unfortunately there was insufficient time under the project to continue work on its development.

4.2.2 Hall Effect Probe

The concept of a Hall-effect probe combined with an optical position indicator was also explored as an alternative extensometer.

Hall-effect devices, along with suitable readout instrumentation, are capable of detecting specific magnetic fields into which they come in contact. Following tests, specific types were selected which worked with the current magnetic sonic extensometer anchors. It was anticipated that the suitable Hall effect device could be attached to a probe which could be fed up the underground borehole to detect the location of the magnetic anchors.

The specific location of each anchor could be identified by attaching an encoded adhesive strip to the probe with specific markings which could be read by an optical source/detector anchored at the mouth of the hole. The readout unit would therefore potentially consist of the instrumentation of the optical source/detector and the Hall effect device that locates each magnetic anchor up the hole.

This system has potential for use as an alternative extensometer. Suitable Hall effect devices were identified during the course of the project. However prior to completion of the project suitable optically encoded adhesive strip had yet to be sourced and matched with a standard optical source/detector system.

4.2.3 Resistance Wire Extensometers – RWE’s

Resistance wire extensometers, RWE’s, provide another alternative to the sonic extensometer in order to measure roof deformation at heights greater than 7.5m into the roof.

RWE’s are produced by Mindata Australia Pty. Ltd. [Mindata, 1997]. A number of RWE’s may be grouted end to end into one borehole in order to measure deformation at intervals into the roof. Typically they are installed into a 50mm diameter hole. Each RWE is secured along the length of a grout tube which is then pushed up the hole. A second short tube is pushed up the hole, the hole then plugged and grout pumped into the borehole. The RWE’s can be supplied in variable lengths from 0.5m long. Thus for the purpose of a replacement to the sonic extensometer, numerous 0.5m long RWE’s could be used, especially in the immediate roof where there are likely to be more strain zones. In the higher roof longer RWE’s could be used.

Recent use of RWE’s in UK coal mines has been reported under an earlier HSE project related to lifting bolts [HSE, 1998]. They were installed at two mines, Asfordby and Stillingfleet, and were used in preference to the sonic extensometer to take advantage of their high resolution of 0.005mm as very small additional roof movements were expected as a result of rockbolt loading trials.
At Asfordby mine two RWE’s, one 1m and one 2m in length, were installed at the two trial lifting sites. These were the anchor type as opposed to the grouted type. A problem in installation was encountered with these as the anchored wire was not always tensioned correctly against the collar plate. The required tensioning could be applied by inserting wedges between the collar plate and roof. This method of taking up the flexure on the anchor was regarded as not totally satisfactory as it could result in over-loading the strain-wire. A modification was envisaged which would allow a more easily controlled adjustment where this type of RWE was required to be installed at other sites. However, despite slight installation problems, all RWE’s operated correctly and no roof deformation was recorded by any of them during the lifting trials on adjacent rockbolts.

During the lifting bolt trials at Stillingfleet mine two 2m long RWE’s were used. Here the RWE’s were read through a data logger which was set for continuous data recording over the specified test time periods. As at Asfordby no roof movements induced by the anchor bolt loading were detected by the RWE’s.

RWE’s can provide high resolution data and are a simple proven tool which is available off the shelf. However unlike the inductive sensor extensometer, if multiple units were used in one hole this would result in multiple wires exiting the borehole. Also at Asfordby the RWE’s were supplied such they could be read with an IS strain metre, but this was not ideal as the ratio of signal to noise was increased although the resolution was unaffected. The data-logger used at Stillingfleet was non-Intrinsically Safe and required exemption for its use underground, but provided a means of continuous data recording for the specific task for which it was employed.
5. LABORATORY TESTING OF STRANDED TENDONS

5.1 INTRODUCTION

The laboratory short encapsulation pull test technique utilising a lathe and biaxial cell, was developed under a previous HSE project, [HSE 2000 (III)]. This has proved to be a successful method of determining bond strength for rockbolt/resin systems in the laboratory. It allows reinforcement systems to be tested in a variety of materials, for example rock, coal or man made material, under stress conditions similar to those of the strata to be reinforced. The lathe based procedure for drilling the hole and bolt installation allows a realistic simulation of drilling conditions and hole rifling as found in-situ. The use of a biaxial cell allows normal stresses to be applied to the rock sample during the test. Under this project the test was further developed including its use to determine the bond strength of grouted tendons.

Section 5.2 describes how the original test method for rockbolt/resin systems was modified for grouted tendons.

In section 5.3 test results for birdcaged cablebolts in sandstone core are presented. Tests were then undertaken on the nutcaged cablebolt and a novel type of stranded tendon called the Australian Megabolt. In section 5.4 tests on birdcaged cablebolts in coal are described.

In section 5.5 tests are described whereby the laboratory short encapsulation technique was used to subject double birdcaged cablebolts to a constant strain once installed. In the normal underground environment cablebolts may be installed into actively deforming/straining roof such that the cables are loaded prior to full development of grout strength. The tests aimed to determine if this affected the reinforcement performance of the cablebolt/grout system.

Section 5.6 describes how the laboratory short encapsulation pull test was adapted in order to carry out pre-tensioning tests on the Australian Megabolt.

5.2 DEVELOPMENT OF THE LABORATORY SHORT ENCAPSULATION PULL TEST FOR GROUTED TENDONS

The technique which has been developed for determining the bond strengths of grouted tendons is similar to that for rockbolt/resin systems with regard to the use of the lathe test rig to drill the hole. Figure 11 shows a comparison between the test set up for rockbolt/resin and tendon/grout systems. The following key aspects of the test procedure for rockbolt/resin systems were modified to accommodate grouted tendons:

(i) use of steel split tubes instead of the biaxial cell,
(ii) increased embedment length,
(iii) development of a satisfactory end arrangement for pull testing,
(iv) method for pulling and recording at high loads.

These modifications are described in more detail below.
5.2.1 Steel Split Tubes for Sample Confinement

Grouted tendon reinforcement systems are normally installed with a cementitious grout which takes up to 14 days to cure to a satisfactory proportion of its final strength. It was therefore impractical to install the tendons into sandstone cores confined by a biaxial cell as each test would effectively put the cell into permanent use for a minimum of 14 days. After a series of trials it was determined that steel tubes with a wall thickness of 15 mm provided a similar confinement and similar test results on standard double bircaged cablebolts compared to the 10MPa confinement applied if a biaxial cell were used. This method was therefore substituted for the biaxial cell, significantly reducing the time the biaxial cell would be required and reducing the cost of the tests. The sandstone cores are grouted into the steel confinement tubes. Latterly these steel tubes have been 'split tubes' which can be reused after each test.

5.2.2 Increased Embedment Length

The length of tendon tested had to be increased due to the nature of birdcaged and nutcaged type cables. With the cage wavelengths being approximately 200 mm long, use of the standard 300mm long core and 250mm encapsulation length as in rockbolt/resin systems, would result in only one cage being tested. This would give unrealistically low bond strengths. The core length was therefore increased to 600 mm to accommodate an encapsulation length of 500 mm.

5.2.3 Gripping Stranded Tendons for Pull Testing

Due to the stranded nature of the long tendons a method was required whereby they could be gripped for pull testing. To overcome this problem the samples ends were pre-cast into a 500mm long steel tube of the same internal hole diameter as used for the test. The length of the tube and its wall thickness were chosen so as to provide adequate confinement and stiffness to prevent failure in this part of the assembly during pull testing.

5.2.4 Pull Testing and Measurement at High Loads

In the case of rockbolts the pull testing takes place while the sample is still on the lathe bed with a hydraulic jack placed over the rockbolt and secured by appropriate conical seats and nuts. The displacement is measured by a dial gauge at the bolt end. Due to the high loads which stranded tendons must be subjected to, up to 60 tonnes, the tests are conducted in a 1000kN test machine. Load displacement graphs are then generated with the displacement being recorded by an LVDT at the joint between the sandstone core and steel pull tube.

5.3 PULL TEST RESULTS FOR STRANDED TENDONS IN ROCK

Three types of stranded tendon have been evaluated using the laboratory short encapsulation pull test. These are the double bircaged cablebolt, the double nutcaged cablebolt and the Australian Megabolt. These three tendon types are shown in Figure 12.
5.3.1 Birdcaged Cablebolts

Following optimisation of the test technique tests were conducted for the double birdcaged cablebolt. A typical result is shown in Figure 13. These results provided a ‘standard’ reinforcement performance against which other stranded tendon types could be compared.

5.3.2 Nutcaged Cablebolts

Figure 13 also shows the typical results for the double nutcaged cable bolt cast in cementitious cablebolting grout in the sandstone core. The double nut cage cables show a much lower bond stiffness and bond strength mirroring the test results achieved when testing such cables in the steel tubes of the Double Embedment Test.

5.3.3 Australian "Megabolt" Cablebolt

The Megabolt is a 60 tonne stranded tendon- grout system. It is a nine wire birdcaged tendon which includes a central 12.7mm diameter steel tube for grouting purposes. The nominal birdcage spacing is 300mm. It has potential advantages compared with conventional cablebolts which include built in grout ports and a tensioning facility. The Megabolt is designed to be installed into fast-set resin at the top of the hole, providing an immediate anchorage, and allowing the system to be pre-tensioned prior to grouting.

It was tested to assess its potential as a long tendon reinforcement system for use in UK mines. It was tested in a 43mm diameter hole and tests were carried out in cementitious grout and AT resin.

Rock/Grout/60 Tonne Megabolt System

Table 1 shows the results of the laboratory short encapsulation pull tests carried out in confined sandstone. Figure 14 plots the results in graphical form and Figure 15 shows photographs of one of the test samples to indicate the mode of failure.

The average peak bond strength for the Megabolt/grout system was 428kN in the range 396kN to 446kN. The average yield bond strength, defined as the strength at which the slope of a load/displacement curve falls below 20kN/mm, was 244kN in the range 191kN to 302kN. The slope of the load/displacement curves is a measure of the stiffness of the Megabolt/rock/grout system for a short length sample.

For the purposes of these tests the stiffness was calculated between loads of 0-100kN, 100-200kN and 200-300kN. The average slope for the Megabolt system was 70kN/mm (0-100kN), 59kN/mm (100-200kN) and 30kN/mm (200kN-300kN).

Rock/Resin/60 Tonne Megabolt System

Table 1 show the results of the laboratory short encapsulation pull tests carried out in confined sandstone. Figure 16 plots the results in graphical form and Figure 17 shows photographs of one of the test samples to indicate the mode of failure.

The average peak bond strength for the Megabolt/AT resin system was 239kN in the
range 220kN to 259kN. The average yield bond strength, defined as the strength at which the slope of a load/displacement curve falls below 20kN/mm was 184kN in the range 173kN to 192kN. The slope of the load/displacement curve are a measure of the stiffness of the Megabolt/rock/resin system for a short length sample. For the purposes of these tests the stiffness was calculated between loads of 0-100kN and 100-200kN. The average slope for the Megabolt system was 25kN/mm (0-100kN) and 14kN/mm (100-200kN).

Table 1 Results for the Laboratory Short Encapsulation Pull Tests on the Megabolt compared with the double birdcaged cablebolt

<table>
<thead>
<tr>
<th>System</th>
<th>Stiffness 0-100kN (kN/mm)</th>
<th>Stiffness 100-200kN (kN/mm)</th>
<th>Stiffness 200-300kN (kN/mm)</th>
<th>Peak bond Strength (kN)</th>
<th>Yield Bond Strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megabolt/grout</td>
<td>59</td>
<td>71</td>
<td>51</td>
<td>442</td>
<td>302</td>
</tr>
<tr>
<td>(Average)</td>
<td>70</td>
<td>59</td>
<td>30</td>
<td>428</td>
<td>244</td>
</tr>
<tr>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Birdcage/Grout</td>
<td>119</td>
<td>61</td>
<td>31</td>
<td>588</td>
<td>315</td>
</tr>
<tr>
<td>Megabolt/resin</td>
<td>23</td>
<td>12</td>
<td>-</td>
<td>239</td>
<td>186</td>
</tr>
<tr>
<td>(Average)</td>
<td>25</td>
<td>14</td>
<td>-</td>
<td>239</td>
<td>184</td>
</tr>
</tbody>
</table>

The results show that the Megabolt system achieved bond strengths and system stiffnesses higher than those expected for single birdcaged cables, but less than could be expected for a double birdcage cable. The results from the tests undertaken in resin show a lower system stiffness, bond strength and maximum load compared to similar tests undertaken in grout. However, this bond strength is more than sufficient to allow pre-tension of 200kN to be achieved prior to grouting, with 1m of encapsulation.

The performance of the megabolt when tensioned, as it is designed to be, are discussed in section 5.6.

5.4 PULL TESTS RESULTS FOR STRANDED TENDONS IN COAL

Following the successful development of the lathe based short encapsulation pull test for tendons in rock the method was adapted to conduct pull tests in coal, so simulating the in-situ conditions found in a coal rib.

Initial laboratory short encapsulation pull tests were carried out using double birdcaged cablebolts. The test procedure was the same as described for use with sandstone core except that the sandstone was replaced by blocks of coal grouted into the steel tubes with cementitious cablebolting grout. Careful packing of the coal pieces, inspection of the drilled holes and splitting of samples after testing indicated that the majority of the hole was drilled through coal.

Figure 18 shows the results from the initial tests. Bond failure did not occur in either test with the cables loading up to their capacity of approximately 60 tonnes resulting in cable failure. These results were better than expected.
It was considered that the use of steel tubes may have provided more confinement than would normally be expected in a coal rib underground. Tests were therefore carried out to investigate an alternative, less stiff confinement tube, thereby refining the test procedure. These results were reported in the previous project, [HSE, 2000 (III)] as tests were undertaken on both rockbolts and tendons (double birdcaged cablebolts). These tests indicated that the chosen plastic tubes resulted in low bond strengths, which were also lower than those previously achieved from tests in coal in-situ at an open cast site. It was concluded that until a more realistic alternative type of confinement tube was identified for simulating the performance of materials in a coal rib, tests would continue using the steel tubes.

5.5 CONSTANT STRAIN TRIALS ON DOUBLE BIRDCAGED CABLEBOLTS

Laboratory trials were undertaken on a double birdcaged cablebolt/grout system using the laboratory short encapsulation pull test technique and subjected to an immediate constant strain. In an underground situation, as soon as a cablebolt is installed, and prior to the grout fully curing, the cablebolt can, in certain geotechnical environments, be subjected to immediate loading. The trials were to investigate how this loading prior to full curing of the grout could affect the cable/grout/rock bond and the ultimate reinforcement performance of the system.

Two trials were undertaken with strain rates of 0.00007 mm/s and 0.00014 mm/s being applied to the end of the cablebolts. The test procedure was the same as under normal circumstances with the exception that once the hole was drilled, the test sandstone core/steel tube assembly was removed from the lathe and placed into the Schenck 2 MN Universal test rig. Enough grout to fill the pre-drilled hole in the sandstone core was then mixed and poured into the hole. A double birdcaged cablebolt was installed into the hole and the embedment tube (pre-grouted on the double birdcage free end) was placed into the jaws of the test rig. A constant axial strain of 0.00007 mm/s was then applied to the end of the double birdcaged cablebolt assembly for a period of 72 hours. The whole test procedure was then repeated with a strain rate of 0.00014 mm/s.

The test results are shown in Figure 19. Results from the first test at a strain rate set at 0.00007 mm/s indicated that a load 550 kN was achieved on the cable at a displacement of 18 mm over the 72 hour period. During the second tests at a constant strain rate of 0.00014mm/s a load of 590 kN at a displacement of 36 mm was achieved after 72 hours.

The results suggest that the cementitious cablebolting grout effectively cures despite the continuous strain taking place. The cablebolts can, therefore, still operate effectively in actively straining roofs. However, although the results indicate a reduced bond stiffness they also suggest that the maximum roof movement prior to cable failure in sandstone in an actively moving roof could be less than 50 mm.

5.6 CABLEBOLT PRE-TENSIONING

The laboratory short encapsulation pull test with sandstone was used to examine the effects of a 20 Tonne pretension load on the performance of an Australian Megabolt
system as described in section 5.3.3. In normal underground practice this cablebolt is resin anchored prior to pre-tensioning and post grouting.

Four 600mm long sandstone cores pre-drilled with 43mm diameter holes were grouted into a 2400mm long steel tube. The hole was then filled with sufficient pre-mixed AT resin to ensure 1200mm of encapsulation. The 2500mm long cablebolt was then inserted and rotated by hand into the hole. After a curing period of 1 hour the cablebolt was pre-tensioned to 20 tonnes and cementitious cablebolting grout pumped into the remaining free annulus.

In the first test, as soon as the grout had been pumped into the pre-tensioned assembly, the tendon was subjected to a slow strain rate of 5mm per 20 hours. In the second test, after curing for 3 days, the assembly was subjected to axial load until failure.

In the first test, Figure 20, for the first 15 hours whilst the load was building up to the 162kN preload retained in the system, no bond displacement occurred, effectively giving an infinite system stiffness. Once the preload had been exceeded, load continued to increase for the next 40 hours to 550kN with a displacement of 3mm giving a working stiffness of 124 kN/mm. For the next 40 hours the tendon continued to yield until failure occurred at a load of 592.5kN with a displacement of 25mm.

For the second case, Figure 21, where the sample was tested following a curing period of 3 days, the system reached a maximum load of 602 kN at a displacement of 24mm. The system stiffness, measured between loads of 200 and 400kN was 182kN/mm. It appears that the pretension in this system was lost during the 3 day curing period. It is not known whether this was due to creep or experimental error and further tests are required to investigate this.

In summary the tests showed that loading after pre-tensioning results in an effectively infinite system stiffness until additional loads are generated within the tendon which exceed the pretension load. The stiffness then equals the unpre-tensioned stiffness, but at a substantially higher loading. Further investigations of the actions and effectiveness of pre-tensioned systems are required to gain an understanding of their applicability and relevance to UK mining conditions.
6. IN-SITU TESTING OF STRANDED TENDONS

6.1 INTRODUCTION

As discussed in section 1.2.4 realistic testing of the complete reinforcement system, i.e. reinforcement, encapsulant and rock, in the laboratory and in-situ, is necessary for the evaluation of the consumables involved and also to derive an improved understanding of the reinforcement mechanisms employed. The laboratory test method provides a fast and cost effective method for determining the performance of novel types of reinforcement and for sensitivity studies on parameters such as hole size, grout strength etc. However measurement of the performance of installed tendons in-situ is required to confirm reinforcement performance within the different strata types into which they are installed. At the time of the initiation of the project no practical underground pull testing system for stranded reinforcement had been devised.

The investigation into such an in-situ pull testing system was divided between a method for birdcaged cablebolts and a method for flexible bolts. Section 6.2 deals with birdcaged cablebolts and section 6.3 deals with flexible bolts.

6.2 BIRDCAGED CABLEBOLTS

A method for pull testing birdcaged cablebolts in-situ was investigated during work carried out prior to the commencement of this research project. Two trials tests were undertaken on birdcaged cablebolts installed at Asfordby Mine. The wires of the birdcaged strand terminated in the plain stranded tail, as per normal, which was used for the attachment of the pull test equipment; the hydraulic jack being placed over the tail and a suitable anchor attached to pull against.

Two pull tests were conducted, with contrasting results. These were considered to be inconclusive with respect to the actual performance of the in-situ strand. This was because there were uncertainties with respect to where the recorded deformation was generated. Deformation would have occurred within the encapsulated length and within the free length. The free length deformation would have been complex with the wires of the strands pulling past each other, so it was uncertain whether the stretch in the cablebolt free length was correctly compensated for.

6.3 FLEXIBLE BOLTS

6.3.1 Method for Pull Testing Flexible Bolts In-Situ

The method for pull testing flexible bolts was adapted from that used for a standard rockbolt. A series of holes are drilled at chosen test horizons and the flexible bolts of the required length installed with a short resin capsule to give an encapsulated length of not more than 300mm.
The pull tests are performed after a curing period of at least 2 hours and not more than 24 hours, after installation. This is to ensure that the resin has time to cure and that no time dependant roof deformation mechanically locks the flexible bolt in the hole.

The equipment used to conduct the pull test and its assembly is shown in Figure 22. This also shows the same set up for a rockbolt. The main difference for the flexible bolt is that a stressing stool is used over the flexible bolt end against which the hydraulic ram is positioned. This is due to the extended length of flexible bolt beneath the roof horizon as a result of the ferrule and torque nut end arrangement.

The analysis of the results from a flexible bolt is carried out in a similar manner to that for a rockbolt. Compensation is made for the displacement within the unencapsulated free length of the flexible bolt.

The test requirements for a flexible bolt are currently the same as for a rockbolt. This is because they are seen as substitutes to rockbolts within the design patterns where they are used. The average bond strength over 50% of the hole length needs to exceed 130kN foe a bond length of 300mm. Typical results from a flexible bolt pull test are presented in section 6.3.2 below.

6.3.2 Typical Results from Flexible Bolt Pull Tests In-Situ

Short encapsulation pull tests were carried out in 301’s Tailgate at Daw Mill Colliery in November 1999 on 4m flexible bolts, using the bolter miner drill rigs for bolt installation. The tests were carried out prior to adopting sole support and were undertaken by the RJB group geotechnical engineer.

The results of applied load against bond displacement are shown in Table 2 for the four horizons tested.

Two tests were carried out at each horizon with Kennametal semi-spade bits using a water flush. The yield bond strength was determined at each horizon and the results from the 2 tests at each horizon averaged as shown in the far right hand column in Table 2.

The results indicate that the average bond strength over 50% of the flexible bolted length exceeds 130kN and that the horizon tested above the AT rockbolt height exceeded 130kN. These tests satisfy the requirements of the guidance on the use of flexible bolts which is currently a draft supplement to the DMIAC guidance document on the use of rockbolts to support roadways in coal mines.
Table 2  Bolter miner flexible bolt pull test results, Daw Mill Colliery, 301's tailgate, 490m

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Test Horizon (m)</th>
<th>Mean Hole Diameter (mm)</th>
<th>Yield Bond Strength (kN)</th>
<th>Mean Yield Bond Strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7 – 1.0</td>
<td>29.2</td>
<td>110</td>
<td>88</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>29.3</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.7 – 2.0</td>
<td>28.1</td>
<td>&gt;230</td>
<td>&gt;220</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>28.3</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.7 – 3.0</td>
<td>28.4</td>
<td>&gt;220</td>
<td>&gt;220</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>28.5</td>
<td>&gt;220</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3.7 – 4.0</td>
<td>29.3</td>
<td>&gt;220</td>
<td>&gt;190</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>29.3</td>
<td>&gt;160</td>
<td></td>
</tr>
</tbody>
</table>
7. CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

Stranded reinforcement tendons have become more commonly used in UK coal mines in conjunction with rockbolt reinforcement. These principally consist of the flexible bolt used at the face of the heading to reinforce ground up to 4m into the roof and cablebolts used as remedial reinforcement for reinforcement up to 10 m in to the roof.

At the outset of the Project the reinforcement mechanisms mobilised by these stranded tendons were less well understood than those of the conventional rockbolt. Through selected areas of research this project has been able to bring the measurement, testing and consequently the understanding of stranded tendon reinforcement significantly nearer to that for the conventional rockbolt.

The conclusions from the research are discussed in section 7.2 under the following selected areas investigated:

(i) Integrity Testing: At the time of commencement of the project there was no method for determining the integrity of stranded tendons already installed in the field. This has been addressed with the RF technique and discussed in section 7.2.1,

(ii) Instrumentation for Integrity and Load Measurement: Instrumentation has been developed that will allow both the integrity and the state of loading in a flexible bolt to be determined, these methods are discussed in section 7.2.2,

(iii) Alternative extensometry: a detailed knowledge of the rock deformation in the ground into which a stranded tendon is installed is fundamental in relating reinforcement strains to ground deformation for correct reinforcement design. Alternatives to the sonic extensometer were investigated, section 7.2.3,

(iv) Laboratory Pull Testing: With the development of different types of stranded tendons suitable laboratory testing techniques were required to improve the understanding of reinforcement mechanisms, these are discussed in section 7.2.4,

(v) In-Situ Pull Testing: How a chosen reinforcement tendon behaves in-situ will in part depend up on the strata conditions in which it is installed, a test parameter that can not be fully simulated in the laboratory, in-situ testing methods for flexible bolts were developed to determine their in-situ bond strength which is critical to a successful reinforcement design, section 7.2.5.

In section 7.3 a summary of how the work has improved our fundamental understanding of stranded tendons is given.

Section 7.4 outlines recommendations for research to increase our understanding of the performance of stranded tendons further.
7.2 CONCLUSIONS

7.2.1 Integrity Testing

The measurement of standing radio wave resonances in in-situ stranded tendons was investigated in order to determine if the method could be used to measure the in-situ length of installed tendons. The measured length would indicate whether the tendon was still intact and thus indicate whether remedial reinforcement action was needed in cases where tendons had failed.

The method was successfully applied in both the laboratory and a limestone mine. The tests undertaken indicated that both an orthogonal and parallel ground plane technique could be used, the later having certain advantages over the former with respect to practicalities and better, clearer results. Despite success in the laboratory and a limestone mine results from a UK coal mine were disappointing. Several refinements to the instrumentation were tried to overcome the problem.

Excellent results were obtained from work at a French coal mine with a limestone roof. This work indicated that the resonant frequencies were very close to the frequency limits of the instrumentation and this could explain the poor results from UK coal mines; the diaelectric properties of coal measures rock generating resonance frequencies on the outer limits of those recorded by the instrumentation.

The Patent Application for the method involving the use of a ground plane method was granted, GB Patent 2 304 417B, and the application for the parallel tendon method is awaiting Substantive Examination.

7.2.2 Instrumentation for Integrity Testing and Load Measurement

**Integrity Testing**

Integrity testing of stranded tendons can also be achieved through instrumentation. Pre-instrumented tendons could be installed periodically as part of the pattern to check on the integrity of a number of tendons along a section of roadway with similar deformation characteristics. Time Domain Reflectometry, TDR, was initially considered as a method for determining integrity, based upon the principal of injecting an electrical pulse into a cable and observing the reflected echo. Knowing the pulse velocity and by measuring the time for the reflected signal to return it is possible to calculate the position of the reflecting surface (tendon break). Although feasible this method would have required complex and expensive equipment and instead it was decided to use an integrity method that was already being successfully used for rockbolts. The “Sentinel” flexible bolt was successfully developed to monitor the integrity of a flexible bolt once installed. These have been successfully manufactured in 4 and 8m lengths.

**Load Measurement**

Assessment of the loading conditions of stranded tendons was required in order to provide vital information on the performance of the chosen reinforcement design.

Work on developing a strain-gauged flexible bolt has been successful, although this took considerable effort. Several initial prototypes were developed in the laboratory. The main problem encountered was associated with the ferrule and torque nut
crushing some of the wires when these were attached subsequent to instrumentation. Further problems were caused during installation trials using hydraulic rigs as the high torque damaged the internal connections. The problems were solved by routeing the wires through 2 diametrically opposite ‘V’ slots and using a barrel wedge for installation purposes. The first strain-gauged flexible bolt was installed in a UK coal mine roof in October 1999 and provided valuable information on the performance of the flexible bolts in that part of the roadway.

**High Strain Measurements**

Investigations were made into the use of extended strain-gauges in conventional (rigid) rockbolts. Replacing the copper continuity-wire of a “Sentinel” bolt with a strain-gauge wire would indicate the increasing overall strain as the bolt approached failure. Several resistance wires connected to different points along the bolt to form “bays” could identify high-strain sectors along the length of the bolt. Results showed that even for localised failures the extended strain-bay could give a measurable indication of failure which is of the same order as that recorded by discrete gauges at the standard spacing of 250 mm. However, because of the averaging effect of such an extended strain-gauge, the interpretation of readings would depend on the assumed strain-distribution (both axial and lateral) within the bolt.

**7.2.3 Alternative Extensometry**

A detailed knowledge of the rock deformation in the ground into which a stranded tendon is installed is important in relating reinforcement strains to ground deformation for correct reinforcement design. Three possible alternatives to the sonic extensometer were investigated, the inductive sensor extensometer, Hall effect probe and resistance wire extensometers, RWE’s. The inductive sensor extensometer potentially has the most advantages with much of the technology having already been developed and tested as part of the remote reading tell tale system. A prototype experienced installation problems but this could be overcome. The Hall effect probe represented another possibility but more investigations are required to reach a prototype stage. RWE’s are tried and tested instruments that can be purchased “off the shelf”. Numerous units could be placed up one hole to form a type of extensometer, however this would lead to a multitude of wires exiting the hole which could effectively limit the number of units i.e. anchors, and unlike the inductive sensor extensometer it cannot currently be read properly with available IS equipment.

**7.2.4 Laboratory Pull Testing**

Rockbolt/resin systems can be tested in the laboratory with a short encapsulation pull test technique using a lathe and biaxial cell to confine the rock. This allows the system stiffness and bond strength to be determined under conditions that are close to those encountered underground. The systems can be tested in different rock materials with hole drilling and bolt installation using the same procedures as underground. Under this project the test method was successfully adapted for testing grouted tendons. The biaxial cell was replaced with appropriate steel split tubes, the embedment length increased and a suitable arrangement to allow the cable ends to be loaded by a 1000kN test machine was developed.

Tests were successfully conducted with standard birdcaged cablebolts installed in cementitious grout in rock, thus producing a standard reinforcement performance with
which other cable types could be compared. Tests were undertaken to compare the performance of a novel type of cablebolt, the Megabolt. This performed well and was recommended for underground trials. The pull test method was also successfully adapted to investigate how installation of cablebolts into an actively straining roof prior to grout cure may affect the system’s appropriate reinforcement performance. The results indicated that despite the active straining, the bolt/grout/rock bond still effectively forms to generate good reinforcement performance. The test was also adapted to investigate pre-tension of a cablebolt system which indicated that this may have significant advantages under certain conditions in UK coal mines.

Tests were also conducted within coal rather than rock to simulate conditions in the coal rib. However the tests results suggested that the steel confinement tubes generated more confinement than normally found in a coal mine rib. Tests in a plastic tube indicated that the particular type of plastic tube chosen provided too little confinement.

7.2.5 In-Situ Pull Testing

How a chosen reinforcement tendon behaves in-situ will in part depend up on the strata conditions in which it is installed. In-situ bond strengths are an important criteria on which a successful design is based. This is a test parameter that cannot be fully simulated in the laboratory. Consequently an in-situ pull testing method was required for both flexible bolts and cable bolts.

A method was successfully developed for flexible bolts, modifying the method used for pull testing rock bolts, thus ensuring that, where they are used, sufficient bond strength is generated up to 4m in to the roof. These tests are routinely carried out where flexible bolts are installed.

A method for in-situ pull testing of cablebolts had been tried prior to the start of this project. This proved to be complex with respect to practically pulling the cablebolt and compensating for the stretch in the steel and movement between the wires of the strand.

7.3 IMPROVED UNDERSTANDING OF STRANDED TENDON REINFORCEMENT

In order to ensure that a chosen reinforcement system is performing adequately to maintain the stability of the roadway it needs to remain intact along its entire length. Once failed at a specific horizon above the roadway additional reinforcement needs to be installed in order to ensure that stability is maintained. Being able to detect whether a stranded tendon is intact is therefore vital to the stability of the roadway. At the commencement of the Project this was not possible. It was only possible to estimate this indirectly based on monitoring of the roadway roof. The RF technique for pre-installed tendons, with current instrumentation, has been proven to be able to clearly identify broken stranded tendons in coal mines with limestone roofs. It is anticipated with modifications to the instrument’s frequency range it will be able to work for coal mines with Coal Measures roof strata.

Instrumentation of stranded tendons prior to installation can provide another means of determining their integrity after installation. The “Sentinel” flexible bolt provides such a method for flexible bolts and can give and indication of the location of the break. It can
be installed at the face of a heading and used to infer the state adjacent flexible bolts in ground that is deforming in a similar manner. More detailed information can be obtained using the newly developed strain-gauged flexible bolt which can indicate the loading profile of the flexible bolt.

The advances in instrumentation of flexible bolts means that the behaviour of the ground and hence stability can be more accurately defined for heights of up to 4m into the roof. At the time of report writing the instrumentation was still only newly available and consequently had not been installed at very many sites. At the site where the strain-gauged flexible bolt had been installed it indicated onset of straining and loading at 3m into the roof. This was just above the rockbolted height and showed that the flexible bolts in the design pattern at 4 m long were successfully providing a high level of reinforcement to the roof where it was required.

The Laboratory Short Encapsulation Pull Test was successfully modified for pull testing stranded tendons. This has allowed comparative tests to be conducted of the currently used bird and nut-caged cablebolts. A novel type of cablebolt was also tested and the results compared with that of current systems. It performed well and was recommended for underground trials in UK coal mines. This type of tests is important in improving understanding of reinforcement behaviour to ensure that only high quality consumables are used underground.

Laboratory tests conducted on a birdcaged cablebolt subject to a constant strain prior to grout curing were conducted to simulate the installation of a cablebolt into an actively deforming roof. These showed that the cementitious cablebolting grout effectively cures despite the continuous strain taking place. Cablebolts can, therefore, still operate effectively in actively straining roofs, albeit with a slightly reduced bond stiffness. The results also suggested that the maximum roof movement prior to cable failure in sandstone in an actively moving roof could be less than 50 mm. This is important for setting monitoring action levels.

The laboratory short encapsulation pull test was also used to conduct tests on a pre-tension cablebolt system. This showed that up until the pre-tension load is reached the stranded tendon system tested had an infinite system stiffness and thereafter a greater system stiffness was achieved for the given load than for the same load without pre-tensioning. The tests indicated that pre-tensioning of stranded systems could improve their performance and this could have advantages under certain load-deformation conditions in UK coal mines.

The laboratory short encapsulation pull test has provided valuable information on the performance of tendons in rock, allowing comparative tests for novel tendon types and sensitivity studies such as the tests carried out on the effect of strain rates on during grout curing. However although it can identify suitable tendon types for reinforcement it cannot totally replace in-situ testing to determine if the strata is suitable for reinforcement. In-situ flexible bolt pull tests are now successfully carried out to on this type of tendon as they often represent a replacement for rockbolts in the primary design pattern.
7.4 RECOMMENDATIONS

(i) The results of this Project, and field monitoring of flexible bolt performance recently undertaken, indicate that flexible bolts of an appropriate design would be suitable for primary support. It is recommended that flexible bolts are fully integrated into the regulatory framework, including DMCIAC guidance and British Standards, as suitable means of supporting coal mine roadways.

(ii) There has been considerable innovation in cable bolting consumables in recent years such as nut caged cables, Garford bulb cables, slimline cables and pre-tensioned cables. It is recommended that the British Standard and DMCIAC guidance are revised to include these innovations within their scope. Any revision of BS7861 Part II should incorporate the Laboratory Short Encapsulation Pull Test as the best available means of assessing stranded tendon reinforcement system performance.

(iii) Work should be undertaken to compare the test results from the laboratory pull test on stranded tendons with results from the field. This will require field results dependant upon (ix) for cablebolts and laboratory test results for the flexible bolt. A comparison of laboratory and field would lead to an improved understanding of how accurately the laboratory pull test system simulates the field conditions and consequently will allow a better assessment of how existing and new stranded tendon types are likely to perform in the field. This will aid appropriate reinforcement design.

(iv) Instrumentation of flexible bolts for integrity and load monitoring has been successful and work should now concentrate on applying the same methods, or an alternative such as TDR to cablebolts. Strain-gauged flexible bolts are now available and it is strongly recommended that, where flexible bolts are installed as part of the designed reinforcement system, flexible bolt loads should be measured in the same way as rockbolt loads in order to validate the design. This should be incorporated in the new DMIAC guidance document.

(v) Comparative tests in coal for rib reinforcement consumables were successful but in reality the system stiffnesses and bond strengths were high compared with those expected in the field. Work should continue to find a suitable confinement medium to simulate more closely the lower confinement found underground in a coal rib compared to that of a roof.

(vi) Following the success of the RF integrity testing method in a French coal mine work should continue on modification to the instrumentation for its successful application in UK coal mines with shaly roof. An extension in the instrument’s frequency range is believed to hold the key to the successful use of the method in UK coal mines. A new ECSC Project is due to start in January 2001 which includes this within its objectives. The RF system, as currently available, can be successfully applied in reinforced excavations in many rock types, including slate and limestone where broken tendons (cables or bolts) are suspected.

(vii) Investigations need to continue on the most feasible replacement to the sonic extensometer. This was identified as the inductive sensor extensometer.
(viii) Laboratory short encapsulation pull tests on a pre-tensioned cablebolt system were successfully undertaken with promising results. Further testing is required to gain a better understanding of the applicability and relevance to UK mining conditions. Enough tests have been completed to justify a field trial.

(ix) Flexible bolts can now be pull tested successfully in the field to assess their reinforcement performance and a method should now be developed for cable bolts.
8. REFERENCES


SCHEMATIC DIAGRAM OF THE PRINCIPAL OF THE R.F. TECHNIQUE FOR DETERMINING TENDON LENGTH

Figure 1
SUMMARY TEST RESULTS FROM THE R.F. TECHNIQUE ON TENDONS TESTED IN A LIMESTONE MINE SLATE CAVERN AND A SCOTTISH COAL MINE

Figure 2
TEST RESULTS FROM THE R.F. TECHNIQUE USED ON TENDONS AT MEYREUIL COLLIERY, FRANCE

Figure 3

4m long installed tendons with higher frequencies indicating that they are broken.
PHOTOGRAPHS OF THE TWO TYPES OF FLEXIBLE-BOLT USED IN UK COAL MINES

FIRTH RIXSON “REFLEX” FLEXIBLE BOLT

EXCHEM “FSR” FLEXIBLE BOLT

Figure 4
STRAIN-GAUGED FLEXIBLE-BOLT WIRES IN A “V” SLOT IN THE KING WIRE, DAMAGED BY CRIMPING
Figure 6

STRAIN-GAUGED FLEXIBLE BOLT STEEL CRIMP AND BARREL AND WEDGE END FITTINGS

(a) Steel crimp and Torque nut

(b) Barrel and Wedge
(a) Strain-gauged flexible-bolt installed with spinner over barrel and wedge system

(b) Removal of spinner for reading the strain-gauged flexible-bolt

INSTALLATION OF A STRAIN-GAUGED FLEXIBLE BOLT IN THE ROOF OF A LIMESTONE TUNNEL
READINGS FROM A STRAIN-GAUGED FLEXIBLE-BOLT INSTALLED IN A STABLE ROOF OF THE LIMESTONE TUNNEL TRIAL SITE

Figure 8
READINGS FROM A STRAIN-GAUGED FLEXIBLE-BOLT INSTALLED IN A COAL MINE ROOF

Figure 9
RESULTS FROM DOUBLE EMBEDMENT SHEAR AND TENSILE TESTS ON A ROCKBOLT WITH EXTENDED STRAIN–BAY INSTRUMENTATION

Figure 10

Tensile failure at 275kN, Shear failure at 225kN
Figure 11

SCHEMATIC DIAGRAM OF THE LABORATORY SHORT ENCAPSULATION PULL TEST FOR
(a) Rockbolt / Resin (b) Tendon / Grout

Sandstone sample 142mm diameter 300mm long

(b) TENDON / GROUT SET-UP

142mm sandstone core grouted into a steel tube

(a) ROCKBOLT / RESIN SET-UP

Pull out displacement measured by LVDT secured to steel embedment tube and placed on sandstone core

Pull out load applied by a 1000kN Tensile Test Machine

10MPa confining pressure applied from hydraulic hand pump

Pullout load applied from hydraulic hand pump
PHOTOGRAPHS OF THE 60 TONNE STRANDED TENDONS TESTED USING THE LABORATORY SHORT ENCAPSULATION PULL TEST

(a) Birdcaged Cablebolt

(b) Nutcaged Cablebolt

(c) Megabolt

Figure 12
LABORATORY SHORT ENCAPSULATION PULL TEST RESULTS FOR A DOUBLE BIRDCAGED AND DOUBLE NUTCAGED CABLEBOLT IN GROUT IN SANDSTONE CORE
LABORATORY SHORT ENCAPSULATION PULL TEST RESULTS FOR A 60 TONNE MEGABOLT ENCAPSULATED IN GROUT

(14 day test, 43mm I/D hole, 500mm encapsulation)
PHOTOGRAPHS OF A 60 TONNE MEGABOLT ENCAPSULATED IN GROUT AFTER TESTING

Shiny area where failure between grout / cable interface occurred

Failure between cable/grout interface
LABORATORY SHORT ENCAPSULATION PULL TEST RESULTS FOR THE 60 TONNE MEGABOLT ENCAPSULATED IN RESIN

Figure 16

(2 Hour tests, 43mm I/D hole, 500mm encapsulation)
LABORATORY SHORT ENCAPSULATION PULL TEST RESULTS FOR DOUBLE BIRD CAGED CABLEBOLTS IN GROUT IN COAL
LABORATORY SHORT ENCAPSULATION PULL TEST RESULTS FOR DOUBLE BIRDCAGED CABLEBOLTS PULLED AT VARIOUS STRAIN RATES

Figure 19
LABORATORY SINGLE 2.4m LONG ENCAPSULATION PULL TEST ON THE 60 TONNE MEGABOLT IN GROUT IN SANDSTONE CORE AT A CONSTANT STRAIN RATE

Max Load 592.5kN
Tendon Failure

Creep Rate 5mm / 20 Hours

Figure 20
Figure 21

Initial pre-tension

Load (kN) vs. Displacement (mm)

Max Load 620.5kN
Tendon Failure

LABORATORY SINGLE 2.4m ENCAPSULATION PULL TEST ON THE 60 TONNE MEGABOLT IN GROUT IN SANDSTONE CORE AFTER 3 DAY CURE TIME

Figure 21
Figure 22

SCHEMATIC DIAGRAM OF THE PULL TEST SET UP FOR (a) ROCKBOLTS AND (b) FLEXIBLE BOLTS