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DESIGN CONSIDERATIONS FOR CABLE TRUSS SECONDARY SUPPORTS IN ROADWAYS OF UNDERGROUND COLLIERIES.

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ABSTRACT

The purpose and current practice of cable trusses in underground coal mines is briefly outlined and details of various cable truss designs are presented. The main part of the paper describes the in-situ performance of cable trusses installed as secondary supports in gate entries and recovery roofs of longwall faces. The performance analysis is based on the results of in-situ monitoring carried out at a number of sites at two underground coal mines within Australia. Truss performance has been assessed as load developed in relation to roof convergence, face position and time. Additionally, the influence of strata conditions, installation pattern/density, roadway layout and geometry have been taken into account.

An analytical model has been developed to predict truss loads. The principal variables are listed and the basis of the model is described. Based upon behaviour observed in the field the model has been progressively upgraded and validated against measured performance.

Guidelines on truss performance and factors which influence it are presented and the implications of these to the use of cable trusses is discussed. Possible methods for improving truss performance in certain strata conditions are outlined and some comments are made on the value of cable trussing compared to cable bolting in these situations.

INTRODUCTION

In the context of Australian underground coal mining, cable bolting has been adopted as the most widely used secondary support method for longwall gate entries and roadway intersections with rigid bar roof bolts being the principal means of primary roof support. There are two basic methods of cable bolting. In the first instance, individual fully grooved cables (with or without plates fitted) reinforce the strata and if plates are fitted can provide some surface support and secondly, cable trusses act to support the roof in a slung like manner.

Most cable bolts are made from 7 wire, 15.2 mm, SRPC strands. Normally two strands are combined to form each cable bolt – a twin strand cable bolt. Originally the strands were used in their plain wound form but now it is more common for the section of the strand which is to be grooved in to the strata to have an open weave or deflected configuration. Individual cable bolts tend to have short (c.3 m) tails' to allow a plate (if required) to be secured onto the cable bolt using barrel/wedge anchors. Cable trusses are formed by installing two or more cable bolts into the roof strata with long 'tails' protruding from the hole collars. These are subsequently interlinked across the roof by passing the 'tails' through holes in a steel block and tensioning them against one another using barrel/wedge anchors. A number of installation and interlinking patterns can be used (Figure 1). The most common type of cable bolt used for truss installations is a twin strand cable with a 7 to 10 m long plain wound 'tail'. These would typically be installed in 50 to 60 mm diameter holes. Two groat types are commonly used; cement based chemical additive grouts which tend to offer the stiffest performance but which frequently require at least a 24 hour cure period before being able to accept appreciable load or pumped resin grouts which may only require a 2 hour cure period to develop equivalent performance. The pullout properties of the cable anchorage are amongst the factors which determine the performance of the truss.

Rigid bar components have also been used to form truss type supports – these usually consist of two roof bolts which are linked across the roadway by a third bar truss member. The roof bolt components of this system may be point anchored or fully grooved. An earlier literature review (Pabianyczyk and Tarrant, 1988) reveals that, particularly in the United States, various terms of truss support have been applied and studied since the late 1960s. However no definitive design criteria appear to have been drawn from this.

This work has focused upon the use of the cable truss or slung system. Its aim was to examine the in situ behaviour of trusses and to identify the factors which controlled this behaviour so that design criteria for cable truss installations and a reliable means of predicting cable truss performance could be established.

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Fieldwork was carried out at Baal Bone and Takenoo collieries to examine the in situ performance of different cable truss installations. The critical aspects of the support mechanism have been identified and incorporated into an analytical model designed to predict the performance or load-bearing characteristic of cable trusses. The model describes the results from the model and their subsequent application. The main conclusions from the field investigations are presented and design guidelines for cable trusses are discussed.

**PREDICTION OF CABLE TRUSS PERFORMANCE**

An analytical model (Fuller and O'Grady, 1990) has been developed to predict the load-deformation characteristic of cable trusses installed in any particular location. Previous work (Pabianeczuk and Tarballi, 1986) concluded that the limitations of physical models were too severe for them to be used for design purposes. The analytical model described here also has limitations but these do not prevent the model from being used as a design tool. The input data required for the model is a mathematical representation of the roof deformation mechanisms and the pullout characteristics of the cable bolt-gouge system under evaluation. Deformation is expressed as a relationship between the closure of the roadway and the size and shape of the loosened zone formed above the roadway. This is determined from simple extensometer measurements within the roof strata. The progressive development of the model has allowed a number of variables to be incorporated, namely:

- the yield of the strand
- the number of strands
- strand type
- roadway width
- hole collar location and spacing
- truss leg inclination
- truss leg length, and
- truss orientation

In its idealized form, the loosened zone above the roadway is assumed to be parabolic in form with a base equal in width to the roadway. The height of the parabola for any given roof deformation is found directly from the roof extensometer measurement described earlier. Truss legs are represented within the model as straight lines (Figure 2). By applying a common co-ordinate system to the excavation, support system and failed zone their geometry can be represented by simple equations. The model has been formulated on the assumption that the portion of the truss legs within the failed zone is effectively "de-bonded" and therefore inactive in terms of supporting the immediate roof. By defining the failed zone and the truss legs with these equations, the portion of each truss leg within the loosened zone can be found for any given roof displacement. In practice the inactive portion of the truss leg may still provide some reinforcement to the immediate roof.

The support load generated by the truss system is related to the stretch of the truss (both in the "de-bonded" portions of the truss legs and the exposed truss segment between the hole collars) which results from the vertical displacements which take place in the roof strata. It is recognized that in some roof strata large horizontal closure can occur across the roof. This causes a substantial reduction in the cable load and reduces the support force that the truss can provide. Therefore, the geometry of the

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Figure 2. Truss Model Geometry

Trusses are not suited to roof conditions prone to large horizontal closure and the model has not been designed to handle the effect of large closure between the hole collars. However, there are cases where small amounts of horizontal closure occur and their influence on the truss support force can be accounted for in the same way as "pull-in". Currently, the model simulates the deformation profile of the exposed roof as the mean of that for a fixed end beam and a simply supported beam. Field measurements have indicated reasonable agreement between this idealisation and the measured profile where the deformation is approximately symmetrical about the centreline. To date the idealisation has resulted in acceptable predictions of truss performance even for sites which have incurred irregular and non-symmetrical roof deformation. However, to enhance the realism and applicability of the model, a sub-routine has been developed to simulate non-symmetrical deformation but this has yet to be validated.

The stress in the exposed truss segment and the "de-bonded" sections of the truss legs depend on the lateral displacement of the hole collar during the deformation of the roof beam. Theory indicates that as the beam deflects downwards its lower surface curves convexly and tension in the lower surface should cause the holes to move apart. However, it has been demonstrated that Coal Measures strata is of low tensile strength and that the development of significant tensile stresses results in the formation of tensile fractures. Field observations made during this work indicated that such cracks were infrequent at the field sites investigated and furthermore, measurement of the displacements between hole collars indicated that no significant lateral movement took place. These observations led to the conclusion that, for the sites investigated and probably for the majority of coal mine roofs, the deformed roof is likely to be in tension but that the magnitude of the tensile stress is very low. It was also concluded from these observations that it was valid to assume vertical displacement of the hole collars in the model.

The algorithm that has been developed to predict cable load is a function of the following parameters:
- the mechanical properties of the steel,
- the final truss geometry,
- the extent of the failed zone, and
- the pullout properties of the cables.

Early testing of the model revealed that the predicted loads were much higher than those measured in-situ. This indicated that the algorithm simulation was too stiff. Field observation had indicated that "pull-in" was a common occurrence at the hole collars. "Pull-in" may be best described as the loaded truss cables cutting into the strata at the hole collars rather than bending around them. Calculations have shown that such "pull-in" may significantly reduce cable stretch from the values predicted by the idealised case and that "pull-in" would have a softening influence upon truss behaviour. It became clear that some numerical assessment of "pull-in" was required in the model to enhance its realism and to provide a justifiable means of "softening" the model's response from that of the initial idealised case. "Pull-in" has been accepted as being a function of the cable load, the truss geometry and the properties of the rock mass. Owing to the complexities of predicting "pull-in", an empirical assessment based on field observations was adopted as the most practical means of incorporating a realistic allowance for it in the model. With the inclusion of this facility the model output now gives the predicted cable force generated with or without the allowance for "pull-in". This may be translated into the total vertical support force offered per strand, cable or truss. An example of the model output is shown in Figure 3. It should be noted that in the example illustrated the cable loads are those for each linked 15.2mm strand whilst the total vertical support force generated is that at each hole collar i.e., the support force generated by each cable bolt (assuming twin strand cables are used). It is important to realise that in the model situation this force is regarded as acting equally at the two reaction points, the hole collars, rather than being distributed across the exposed truss. There may be some vertical support provided between the hole collars but this will usually be small compared to the vertical force at the hole collars.
Field observations revealed that truss performance could also be influenced by the incorrect placement and installation of barrel/wedge anchors used to interconnect the cable strands. Incorrect positioning of the wedges within the barrels reduces the gripping efficiency onto the strand and allows the strand to slide further through the anchor before the wedge locks onto the strand. This action effectively 'softens' the truss's load-deformation characteristic without reducing its overall capacity. The model has the capability to examine the impact of this and other similar 'softening' influences.

FIELD INVESTIGATIONS

Four mine site investigations have been undertaken at two NSW coalfields to examine the behaviour and measure the performance of cable trusses installed as secondary supports in longwall gate roads. The sites covered a range of ground conditions and truss installations featuring different grout and bolting patterns.

Instrumentation was initially designed to monitor the force development in the exposed truss segment in response to strata deformation. However, with increased understanding of the critical aspects of truss behaviour, such as 'pull-in', and in order to validate some of the assumptions in the analytical model additional instrumentation was included. This was designed to measure the force developed in the greater sections of the cable bolts, the deformed profile of the roof and lateral closure of both the roof strata and the exposed truss segment between the hole collars.

Details of the field investigations are shown in Table 1.

BAAL BONE COLLIERY

The results from the investigations at Baal Bone Colliery (Faller and O'Grady, 1991) were consistent in that at both sites low levels of truss force corresponded to low levels of deformation within the bolted horizon. This concurs with the theoretical prediction that deformation or stretch of the exposed truss segment is a necessary prerequisite for force to be generated in the truss. Low force development in the exposed segment does not preclude the fully grouted cables, which form the truss legs, from offering significant reinforcement to the roof strata at horizons where movement occurs. The apparently secure bonded portions of the cable above and below the 3m roof horizon would provide adequate anchorage for the cables to achieve high forces to resist the deformation at this horizon. Attempts to monitor the reinforcement loads generated in the truss legs were unsuccessful in the SE Malagait owing to lead wire damage; but improved instrumentation allowed this behaviour to be monitored successfully at Talmoor Colliery.

Twin strand cable trusses at Baal Bone were installed with a pumped resin grout and were interlinked directly across the roadway. The low levels of deformation in the bolted horizons at this instrumented site are likely to be due to the use of fully encapsulated, high strength (X-Bar) bolts as primary support. In other areas of the colliery where lower strength bolts were used, high levels of roof deformation had occurred and the exposed segments of trusses installed in these areas were observed to be under significant tensile loads.
Table 1 Field Site Locations and Instrumentation

<table>
<thead>
<tr>
<th>COLLIERY</th>
<th>LOCATION</th>
<th>INSTRUMENTATION</th>
<th>COMMENTS</th>
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<tbody>
<tr>
<td>Basal Bone</td>
<td>LW 4 Expressway (Mid-fact takeoff road)</td>
<td>5 x Sonic Probe Extensometers 2 x Tensile-70 Truss load sensors</td>
<td>Displacement up to 7m into the roof. Probable movement of datum point. Movement within lower 3m of roof strata. Initial load loss in upper segment followed by slight increase.</td>
</tr>
<tr>
<td>Basal Bone</td>
<td>EE Maingate Longwall 8 Outside Cut-through 20 Tussted Zones</td>
<td>3 x Sonic Probe Extensometers 2 x Tensile-70 Truss load sensors</td>
<td>Very low displacements; maximum 30 mm. Lesser 3m of strata behaved as a block. Very small load increase in exposed upper segment.</td>
</tr>
</tbody>
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| Tahmoor | LW 5 Maingate - Belt Road (4 Sites) | At each site 1 x controlled Sonic Probe Extensometer, 10 or 12 x Tensile-70 Truss load sensors | Normal Longwall retreat. Significant load development. Truss loading apparently related to nature of strata deformation and position. |

| Tahmoor | LW 7 Maingate - Belt Road (4 Sites) | At each site 1 x controlled Sonic Probe Extensometer, 4 or 6 x Tensile-70 Truss load sensors, strain lateral displacement stations, Roof deformation levelling stations not, at one site 4 x Blodejage strain cells (to monitor reinforcement loads in the truss legs) | Interrupted Longwall retreat. Roof fall in adjacent travelling road. Loading trials in area of very weak roof strata disturbed by low angle bedding plane faulting. |

TAHMOOR COLLIERY

Two large scale investigations were carried out at the Tahmoor Colliery. Truss installation at Tahmoor differed from Basal Bone in that the exposed truss segments were interconnected in a cross-over pattern and the trusses (twist strata, open weave cables) were installed using a cement based grout with chemical additives. The trusses in both investigations were installed on nominal 2m centres. Four sites were established for each investigation the first of which was located in the belt road of Longwall 5 (O'Grady, Roberts and Fuller, 1991). The aim was to obtain performance data for this truss configuration and compare it with the behaviour of the Basal Bone style of truss.

The second investigation performed at Tahmoor was carried out in the belt road of Longwall 7 (Fuller, O'Grady and Weismann, 1991). This featured a comprehensive instrumentation layout designed to confirm and measure the truss mechanisms which had been identified by the theoretical simulation and the analysis of results from the previous field sites. These were the deflected profile of the roof beam, "pull-in" of the cables at the hole collars, lateral closure across the roadway and load development within the bonded sections of the truss legs (Figure 4). Levelling measurements were also made to independently check the stability of the extensometer datum magnet.

The main conclusions from the Tahmoor studies were that:

- Long term force development in trusses only occurred where a coherent band of strata was observed in the bolted horizon. The integrity of these bands caused them to behave like beams and allowed the strata to deflect more like a single unit. Where cables were located in areas of favourable strata then low force development was measured in cables.

- Cable truss loading is related to longwall face position and therefore probably abutment strata influence. In Longwall 5, where a regular face retreat occurred, the rise in truss loads at Sites #1, #2 (Figure 5) and #3 consistently indicated that the influence of the strata abutment commenced about 20-23 m ahead of the face. However, in Longwall 7, which was subject to interrupted working, wide variations occurred in the truss load-longwall face displacement patterns. It is probable that the delays and interruptions to face retreat caused the influence of the abutment to extend over a progressively larger area. The loading patterns of the trusses in Longwall 7 were consistent in that load build up at all four sites commenced during the same 4 day period which included a two day stand period. The fall in the travelling road occurred during day shift of the second day. Either or both events may have influenced the truss loading patterns.
The prolonged exposure of the supported roof to the influence of the front abutment stress referred to above caused fragmentation of the strata. This allowed the lower roof to unroll around the support members rather than acting against them.

During both investigations, cables attained significant loads up to and exceeding the yield capacity of the strand. This indicates that the cable anchorage was secure but that at the installed densities there was a potential for the strata load to exceed prestress load capacity and for strata failure to occur.

The deformation noted in the bolting horizon during both investigations, particularly the large downward displacements and shear movements noted in Longwall 7, indicated that the primary supports had a limited effect in maintaining the immediate roof strata as a continuous beam.

Significant lateral closures across the roadway did not occur at any of the Tahmoor sites. The principal softening (or load reduction influence) on the cable trusses was "pull-in". This was observed to be a progressive phenomena and is probably the cause of the cyclic loading and unloading behaviour observed in some trusses.

If zones of fractured, disturbed or otherwise very weak strata are to be supported with cable trusses then additional measures to ensure adequate load transfer must be applied. Measuring the use of injected grouts and resins could be considered as means of preventing the strata unraveling around the trusses.

At the sites investigated the extensometer datum marks were not stable. This indicated that the failure zone above the roadway extended above the 7.2 m horizon and also that the measured displacements are in fact relative and not absolute.

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DESIGN GUIDELINES FOR CABLE TRUSSES

The installation of cable trusses or slings is generally preferred over the installation of individual cable bolts where the degree of fracturing and looseness in the roof is so intense that good bond development is difficult to achieve. Under such conditions, cables cannot develop an adequate "connection" to the roof strata and so strata reinforcement is not efficient. Typically this is the case in highly laminated or fractured strata. Truss cables can be installed into the unisononed strata over the ribends which permits effective gouging of the cables and allows a secure "connection" to be made between the cables and the strata. Despite this, a truss system will not prevent large deformations, it's main purpose is to minimise the risk of a fall by capturing the deformed rockmass in a crumpling manner. This mechanism is only efficient if the deforming strata bears effectively against the exposed truss segment to generate a support force. Field observations and results have indicated that the load transfer is most effective if a composite beam can form within the lower regions of the bolted horizon. If the bolted horizon becomes totally fragmented then the strata can simply unravel around the trusses rather than acting against them. If these conditions are predicted then load transfer may be assisted by placing mesh above the trusses or by consolidating the ground using injected resins or gels.

The cable truss system cannot resist or reduce the impact of either in-situ horizontal stresses or mining induced stresses on the development of the yielded or loosened zone. Cable trusses are best considered as support to control the strata movement once the roof has failed rather than having any real capacity to prevent the failure or the realisation of the strata. Notwithstanding this, if bucking of the failed strata occurs to some degree then (if load transfer is adequate) it is probable that the confinement offered by the truss to the failed strata will ultimately restrict the extent of the failure. It is not practicable to use a truss as an active support whereby a positive force analogous to the actuating load of a powered support is applied to the strata through pre-tensioning of the interlinked truss cables. Although field measurements have indicated that it is possible to install a truss with a tension of 4 to 5 tonnes, subsequent monitoring has indicated that this load is quickly dissipated. Truss systems should be regarded as purely passive supports in which the generation of support forces is a reaction to downward roof movement. Trusses are not effective where roof strata is prone to high horizontal closure as this dissipates tension in the trusses and reduces support force.

Accordingly the design of a truss system can be based upon the following parameters:

- the total load carrying capacity of the truss system,
- load transfer between the strata and the cables,
- effective stiffness of the truss system, and
- cable anchorage.

A series of guidelines has been formulated to describe how these parameters and the variables which control them can be adjusted to optimise truss performance. Particular truss designs are site specific. Whilst variables such as hole collar location and cable inclination can be adjusted to optimise the design they will frequently be dictated by practical difficulties such as restricted drilling access and group placement in fractured strata. Where this is the case these factors should be regarded as fixed constants and the design optimised by adjusting only the remaining variables. The parameters listed above are interdependent and none of them can be varied without affecting one or more of the others. Whilst it might be convenient to consider them individually in the design, the overall impact of each alteration must be examined.

The installed load capacity of the truss system is determined by considering the maximum displacement that is allowable before the driving force is at least balanced by the support force. For a passive support system, the maximum driving force might be assumed to be the deadweight, gravitational load of the loosened strata contained within the failed zone. In reality the driving force would probably be less than this as the loosened material is likely to be self-supporting to some extent. However it is impossible to determine the extent to which this will occur and if the truss is to fulfill its purpose of minimising the risk of a fall it must be capable of supporting at least the maximum load. Driving forces for design must be derived from theoretical deadweight loads and then appropriate factors of safety applied. The theoretical deadweight load can be calculated by considering the volume of failed strata per linear metre of drivage and its bulk density. Once the design driving force per linear metre has been established, a number of different truss configurations can be evaluated to select the best option to achieve the required support force capacity at an acceptable roof displacement, truss density and cost.

The variables which control the four main parameters are:

- the lithology and structure of the proximate strata and their effect on bond performance at the grout/cable and grout/strata interfaces,
- cable inclination,
- hole collar location,
- cable length,
- the extent and shape of the failed zone,
- trussing pattern.
the deformed roof profile, and

- the impact of softening influences such as "pull-in" or slip of the barrel/wedge anchors.

The first parameter relates to the cable anchorage capacity and the pullout performance of the anchor. Controlled bond length pullout tests are used to determine the pullout stiffness of the truss cables and the total anchor capacity per unit length of cable. Cable inclination and hole collar location also have a bearing on this because they determine the length of cable outside the loaded zone. This is the only portion of the cable which is considered to be "anchored". The truss system must be designed so that for the largest possible loaded zone, sufficient length of each cable will remain bonded to give an anchor capacity in excess of the minimum breaking force of the cables. The inclination of the cables determines the component of the cable load which can act as a vertical support force against the loosened strata.

The stiffness of the truss system is primarily influenced by the "free length" of cable, i.e., the unbonded length of the cable which is free to stretch and hence build-up tension. The "free length" is the portion of the truss legs which are unbonded plus the length of the exposed truss segment. In its softest form the truss is considered to be a point anchored system where the portion of each cable within the loaded zone is totally debonded. As the "free length" increases, the truss response will soften i.e., greater roof deformation will occur before the support load equals the driving force. This could imply that, for example, direct tunnelling with closely spaced holes would be stiffer than cross-cut tunnelling with the holes placed near to the ribs. However, this is not necessarily the case as shortening the length of the linked segment by placing the hole collars close together results in an increased debonded length of cable within the loaded zone so the total "free length" is not necessarily reduced.

Direct tunnelling will offer a stiffer response than cross-cut tunnelling for the same hole spacing but this benefit is counteracted by the improved roof coverage offered by the cross-cut pattern. Field observations have indicated that the interaction of cables with W-steeples (which normally only occurs with a cross-cut pattern) reduced "pull-in" and offered potential for improved load transfer. Roof coverage by cable trusses is often limited by operational restrictions on hole collar location. The second determinant of truss stiffness is the pullout characteristics of the debonded cable from grouted anchor found from the controlled bond length pullout tests. Thirdly, hole collar location can have a significant bearing on the stiffness of the truss with collars in zones of high or rapid deformation allowing the support force to build-up more quickly in many cases. To help prevent the location of the hole collars being dictated by practical considerations it is advantageous to install trusses in an unobstructed roadway.

The final factors to be considered are the softening influences of "pull-in" and slip in the barrel/wedge anchors. Figure 6 shows three support response curves: the idealized curve for a hypothetical true installation, the same installation with an allowance for "pull-in" and firstly, the impact of slip in the barrel/wedge anchor. "Pull-in" occurs when the rock bearing against the cable fails at the hole collar. This causes the cable to cut into the rock either in a continuous, gradual manner or as sudden, isolated events. "Pull-in" reduces cable tension and hence support force. As yet no practical, economic means of preventing "pull-in" has been devised and it should be assumed that it will occur and an allowance for it should be included in the design. Slips in the barrel/wedge anchors are most commonly caused by the incorrect positioning of the wedges in the barrel. Ideally the wedges should be placed evenly in the barrel so that their ends are level and there is an even gap between them. Failure to achieve either one or both of these conditions is likely to allow cable to slip through the wedges for some distance until adequate grip is achieved to prevent slip.

Although the analytical model has been based on a number of assumptions, it has been found to be a useful method for investigating the sensitivity of truss performance to installation geometry, pullout characteristic and failure zone development and as a design tool to allow truss densities to be defined for various roof loading conditions.
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