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Composite Steel Wire Ropes for Mine Hoisting Applications

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ABSTRACT

The level of wire rope technology used in mine hoisting applications has a significant effect on the overall efficiency of the hoisting system. This paper discusses the effect that a reduction in rope mass per unit length and an increase in rope breaking strength can have on rock skip capacity and hence mine shaft output. A 20 per cent reduction in rope mass per metre for a typical 48 mm hoisting rope, while maintaining the breaking strength, increases the skip's capacity by circa 30 per cent at a suspended rope length of 3000 m. Such gains in shaft output, without any significant changes to the shaft or winder design, can have major implications for the feasibility of future deep mine projects. The technical challenge for rope manufacturers is how to get rid of 20 to 30 per cent of the rope mass while keeping the breaking strength and modulus of elasticity of the whole rope constant. CASAR are currently developing steel wire rope constructions where the steel IWRC has been replaced with high strength, high modulus fibres such as Kevlar®, Spectra® and Dyneema®. One of the key aspects of such composite rope designs is to ensure equal load sharing between the different rope components, ie in proportion to their area. If there is a significant difference in modulus between the fibre core and the steel outer strands, the core may not carry its proper proportion of the load and the outer strands would be overloaded. Some technical aspects of the design of composite steel wire ropes are discussed. A design and operational issue that needs careful consideration is the safe non destructive testing (NDT) of composite ropes. Traditional magnetic NDT would only be capable of inspecting the steel wires. Techniques therefore need to be developed that would give operators a reliable indication of the condition of the load bearing fibre core. This paper also discusses possible solutions to this very important NDT question.

INTRODUCTION AND LITERATURE REVIEW

This paper is concerned with the concept of composite ropes for mining applications. The term composite rope implies a rope that is a steel and fibre combination rope, where the fibre in the rope is either of an aramid type (eg trade name Kevlar®) or high modulus polyethylene (eg Spectra® and Dynema®), which have very high breaking strengths associated with low stretch and low densities (compared to steel).

The idea of combining high strength fibres with steel wires in a rope construction is not new. In 1977 a UK patent (GB1578858) was filed entitled 'Wire-rope with load-carrying core fibres', which described a steel wire rope incorporating a core of aromatic polyamide fibres, which act as load-carrying elements and are lubricated. Several years later Klees, Hoganson and Data (1989) described a composite steel wire rope in their US patent, which is exactly the configuration proposed by CASAR for mining applications, with some minor modifications. Figure 1 shows the cross-section of the Klees, Hoganson and Data rope structure, which includes a jacketed Kevlar® core.

The rope was described by Klees, Hoganson and Data as:

> *A composite wire rope comprising a plurality of outer strands laid helically about a helically stranded core. The core is comprised of high-strength synthetics, such as polyamide or polyolefin materials to form a unitised lay central member. The method for forming the rope comprises the steps of twisting high strength synthetic monofilament yarns into core elements to provide a high degree of stability and overall tensile strength. Each such element is helically laid in a single operation to form the finished core. Lubricant may be applied and subsequently a protective jacket of steel, natural or synthetic material may be provided to encapsulate the core and lubricant. The rope structure is completed by helically laying a plurality of outer strands about the core.*

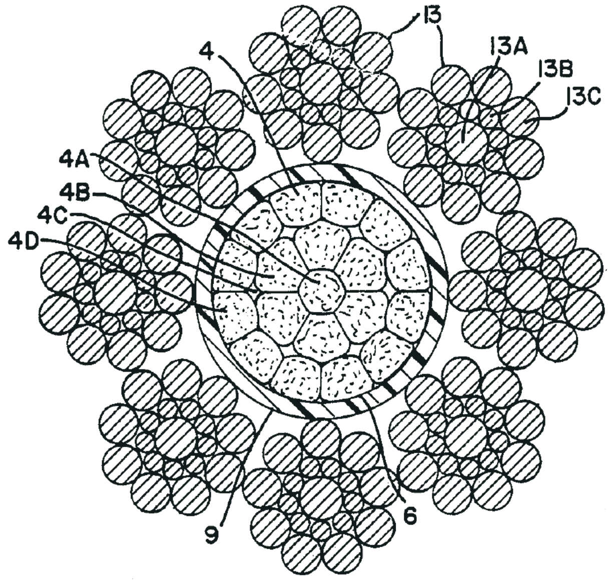

FIG 1 - Composite steel wire rope as proposed by Klees, Hoganson and Data (1989) in their US patent filed in September 1988. 4 - Kevlar® core and core elements, 6 - Lang's lay coated fibre core, 9 - core protective coating, 13 - steel outer strands.

An extension of the composite rope theme is the tapered mass rope proposed by McKenzie (1990). This involves progressively removing steel from the rope to reduce its mass (and breaking strength) while maintaining the overall rope diameter (see Figure 2). The motivation for this design is that in deep vertical shafts less rope strength is required at the conveyance than at the head sheave as a result of the suspended rope mass. In theory a rope could be constructed that would have varying metallic cross-sections, and where the wires in the strands are progressively replaced by polymer fibres or rods. Unfortunately the practical problems of manufacturing such a rope and ensuring its integrity during operation have prevented one ever being manufactured. It would appear that in general a composite rope, like that proposed by Klees, Hoganson and Data and others, is a more realistic solution for enhancing the performance of deep shaft hoisting systems.

More recently authors such as Dolan (2003) have discussed how high-strength carbon fibres can be used to enhance the properties of wire ropes in applications where special mechanical properties

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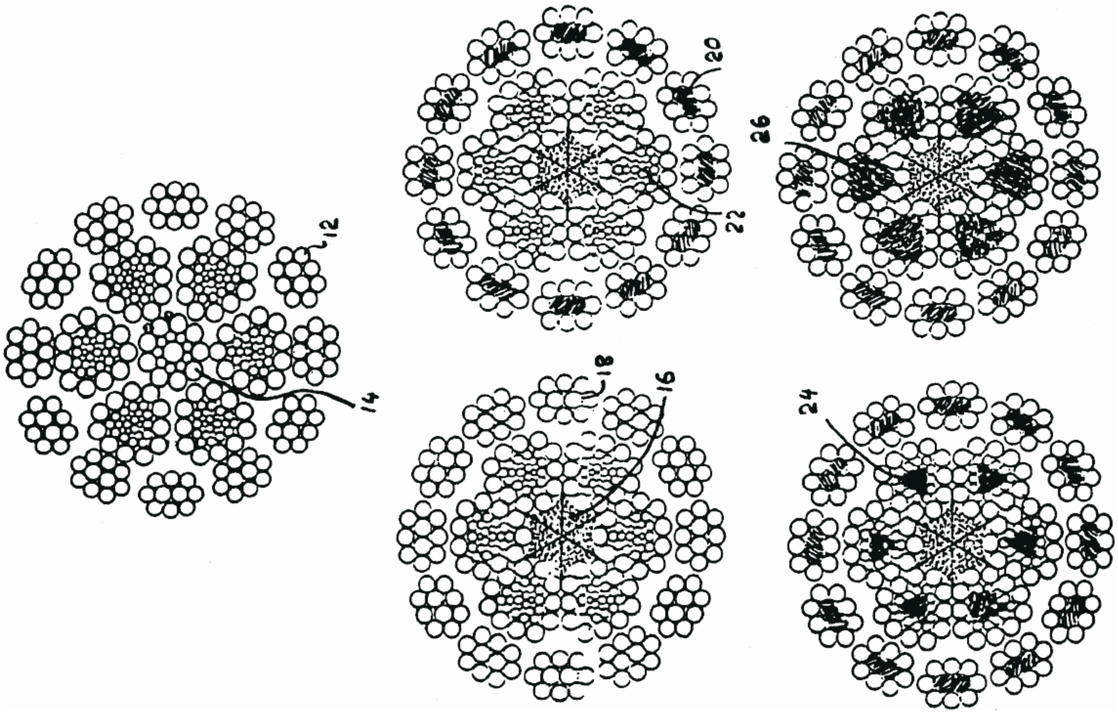

FIG 2 - Reduced or tapered mass rope as proposed by McKenzie (1990) for deep shaft mine hoisting applications. The five cross-sections show progressive replacement of steel with polymer material moving down the shaft. 12 - fishback wire strand, 14 - steel wire rope core, 16 - synthetic fibre rope core, 18 - outer steel wires, 20 - synthetic fibre strand core, 22 - steel wire strand core (triangular), 24 - synthetic strand core (triangular), 26 - extended synthetic strand core (triangular).

are needed that are not provided by steel-only constructions. There is also a substantial body of literature that deals with the application of high-strength fibre ropes (ie fibre only) in various applications, such as elevator systems and offshore mooring. Examples include the book by Hearle, O'Hear and McKenna (2004), which gives a broad description of the design and application of fibre ropes, and Olsen and O'Donnell (1999) where the use and magnetic inspection of Kevlar® elevator ropes is described.

However, for mining applications it is unlikely that fibre-only ropes will be robust enough to withstand handling during installation and maintenance operations. Deterioration on multi-layer drums will also be a limiting factor. It is for these reasons that the authors are proposing the use of composite steel and fibre ropes, which would combine the robustness of a steel rope with the weight saving properties of fibre ropes. In the sections that follow, a discussion of the potential benefits of composite ropes to the mining industry is given and an example of a design of a composite TURBOPLAST rope for drum winding applications is presented. This is followed by a brief examination of issues relating to the effective non-destructive testing of composite ropes and some developments in high strength fibre synthesis that could revolutionise rope design for mining applications.

THE SIGNIFICANCE OF ROPE WEIGHT REDUCTION AND STRENGTH INCREASE ON MINE SHAFT OUTPUT

The level of wire rope technology used in mining applications can have a significant effect on the overall efficiency of the hoisting system. In this section, examples are given of the effects that reductions in rope mass per unit length and increases in rope breaking strength can have on rock skip capacity.

Figure 3 shows a typical configuration of a drum winder for hoisting rock in a vertical shaft. Starting with standard rope constructions used for these applications, it is clear that increases in the strength to mass ratio of the ropes would have a positive effect on the efficiency of the winder and on shaft output capacity.

Opportunities for rope improvements

Two possibilities exist for improvements in the rope strength to mass ratio for a given rope diameter:

1. lighter ropes with the same breaking strength, and
2. stronger ropes with the same mass per unit length.

In order to investigate the effects of the above two variations, it is necessary to make some assumptions regarding the winding system. The two most important values in determining skip capacity for a given hoisting rope are the allowed static factor of safety and the skip factor or ratio between the empty skip mass and rock payload. For the calculations here the following values have been assumed:

$$SF = \frac{Rope\ Breaking\ Strength}{Maximum\ Static\ Rope\ Load} = \frac{25\,000}{4000 + L} \quad (1)$$

$$f_{skip} = \frac{Empty\ Skip\ Mass}{Rock\ Payload} = 0.7 \quad (2)$$

The static factor of safety (SF) equation dependant on the maximum suspended rope length (L) represents the latest technology for the South African mining industry, SANS (2000). The skip factor of 0.7 (f_{skip}) is a typical value for the design of rock skips for drum winders.

With these assumptions made, a simple equation for the rock payload (M_p) can be determined in terms of the minimum rope breaking strength for design (MBL), the rope mass per unit length (ρ) and the skip factor (f_{skip}) and maximum suspended length (L):

$$\frac{25\ 000}{4000 + L} = \frac{MBL}{M_p + f_{skip}.M_p + \rho.L}$$

$$= \frac{MBL}{M_p.(1 + f_{skip}) + \rho.L} \qquad (3)$$

$$M_p = \frac{MBL.(4000 + L)}{25\ 000.(1 + f_{skip})} - \frac{\rho.L}{(1 + f_{skip})}$$

For most ropes the *MBL* is reported in units of kN, so for the payload in kg, Equation 3 would become:

$$M_p = \frac{\frac{MBL.1000}{9.81}.(4000 + L)}{25\ 000.(1 + f_{skip})} - \frac{\rho.L}{(1 + f_{skip})} \qquad (3a)$$

Lighter ropes with the same breaking strength

Using Equation 3a it is possible to investigate the effects of changes in *MBL* and ρ on the skip payload, M_p. Starting with typical parameters for a mine hoisting rope, Figure 4 shows how skip capacity varies with depth and reduction in rope mass per unit length. Note that the zero per cent line represents the initial conditions that would be achieved with the standard hoisting rope technology.

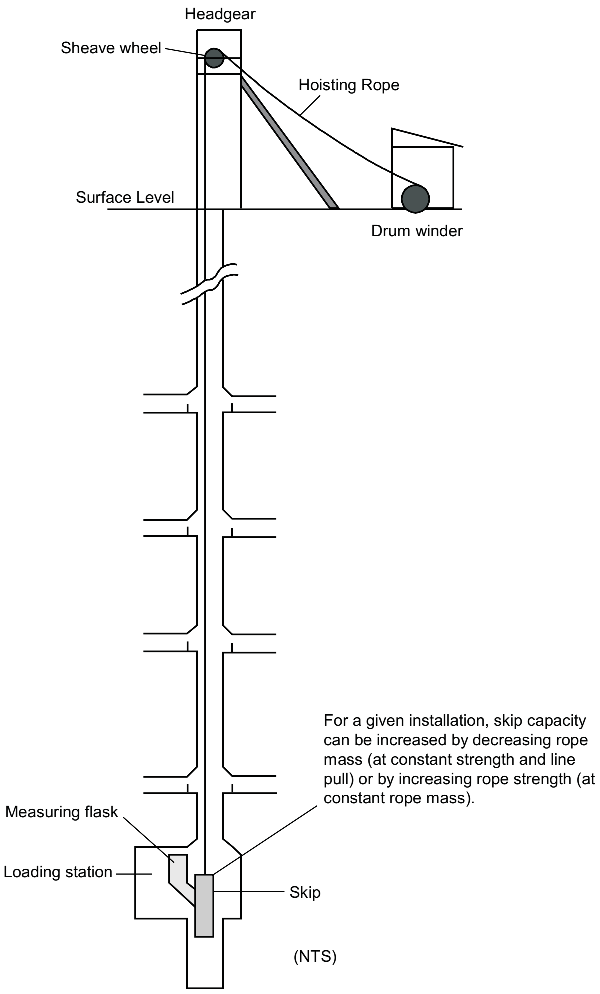

FIG 3 - Typical vertical shaft rock winder configuration. Current shaft depths range from a few 100 m to 3000 m in a single lift for gold mining in South Africa.

It is of interest to note that because the static factor of safety is decreasing with depth, Equation 1, there is a unique rope strength to weight ratio, which would allow for constant skip capacity at all shaft depths. Examination of Equation 3 shows that when MBL/ρ = 25 000 m, the skip capacity becomes independent of the suspended length (*L*):

$$M_p = \frac{MBL.4000}{25\ 000.(1 + f_{skip})} \qquad (3b)$$

By comparing the skip capacities for reductions in rope mass per unit length (ie five per cent, ten per cent, etc) to the standard rope technology (zero per cent) in Figure 4, it is possible to determine the effect of the reduction in mass on the percentage increase in capacity. This gives an indication of the significance of the changes. Figure 5 shows the results of such calculations.

A 20 per cent reduction in rope mass per metre at 3000 m increases skip rock capacity by 29 per cent. By the way in which this was calculated, the value automatically takes into account the increase in skip mass required for the additional rock. The winder parameters would stay more or less the same because the rope line pull remains unchanged (ie unchanged diameter and breaking strength).

Stronger ropes with the same mass per unit length

Figure 6 shows how skip capacity varies with depth and an increase in rope breaking strength. Note that the zero per cent line again represents the initial conditions that would be achieved with the standard hoisting rope technology. Although not shown in the figure, in this example an increase in strength of 39.5 per cent would result in the capacity becoming independent of the maximum suspended length (*L*), the condition described earlier by Equation 3b.

Based on the data in Figure 6, Figure 7 shows the effect on skip capacity when the ropes with higher breaking strength (same diameter and mass) are compared to the typical condition (zero per cent).

In the case of a 20 per cent increase in breaking strength, with unchanged mass per metre at 3000 m, skip rock capacity increases by 50 per cent, which is significant. Changes to the rope breaking strength imply higher line pulls for the same static factor of safety and so the increases in capacity in Figure 7 would require changes to the design of the winding machines. For a fixed number of skips per month, shaft output and the increase in skip capacity are directly related. So, if the capacity of the skip goes up by 50 per cent, then in theory the shaft output would also increase by the same amount (assuming mining can support this).

Lighter and stronger ropes

It is also possible to consider a combination of a reduction in rope mass with an increase in strength. When using the previous two values of 20 per cent decrease in mass and a simultaneous 20 per cent increase in strength, the skip capacity would increase by 79 per cent at 3000 m (this implies a rope with a *characteristic length*, MBL/ρ, of 26 890 m).

Existing installations and capacity factors

If composite ropes are to be applied in existing installations then maintaining rope diameter is important so that sheaves and drum sleeves do not need to be changed. The discussion in this section has not considered the effects of capacity factor, which is applied in some jurisdictions like South Africa, under the conventional mining regulations. When the factor of safety, as defined in Equation 1, is applied then the capacity factor is not used.

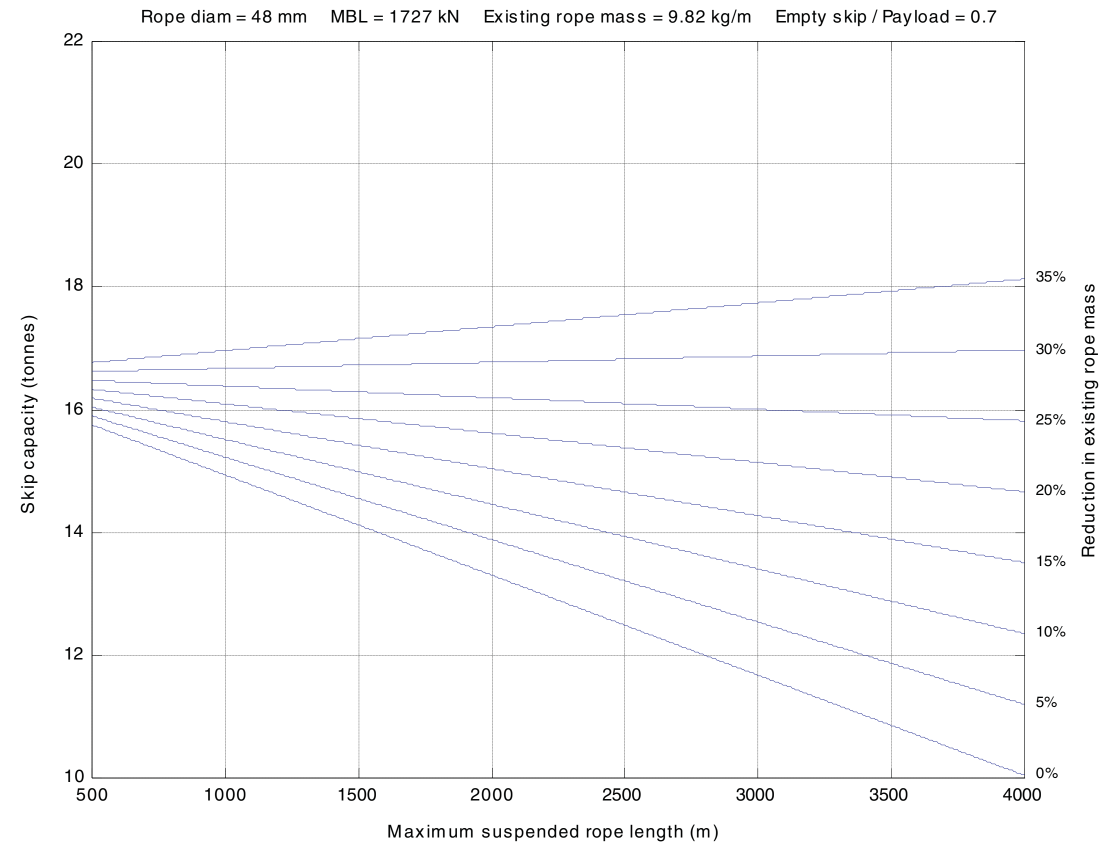

FIG 4 - Calculated skip capacity based on typical mine hoisting system parameters for vertical shaft drum winders. The family of curves show the effect of reductions in rope mass per unit length, with maintained diameter and breaking load (*MBL*), on the skip rock capacity.

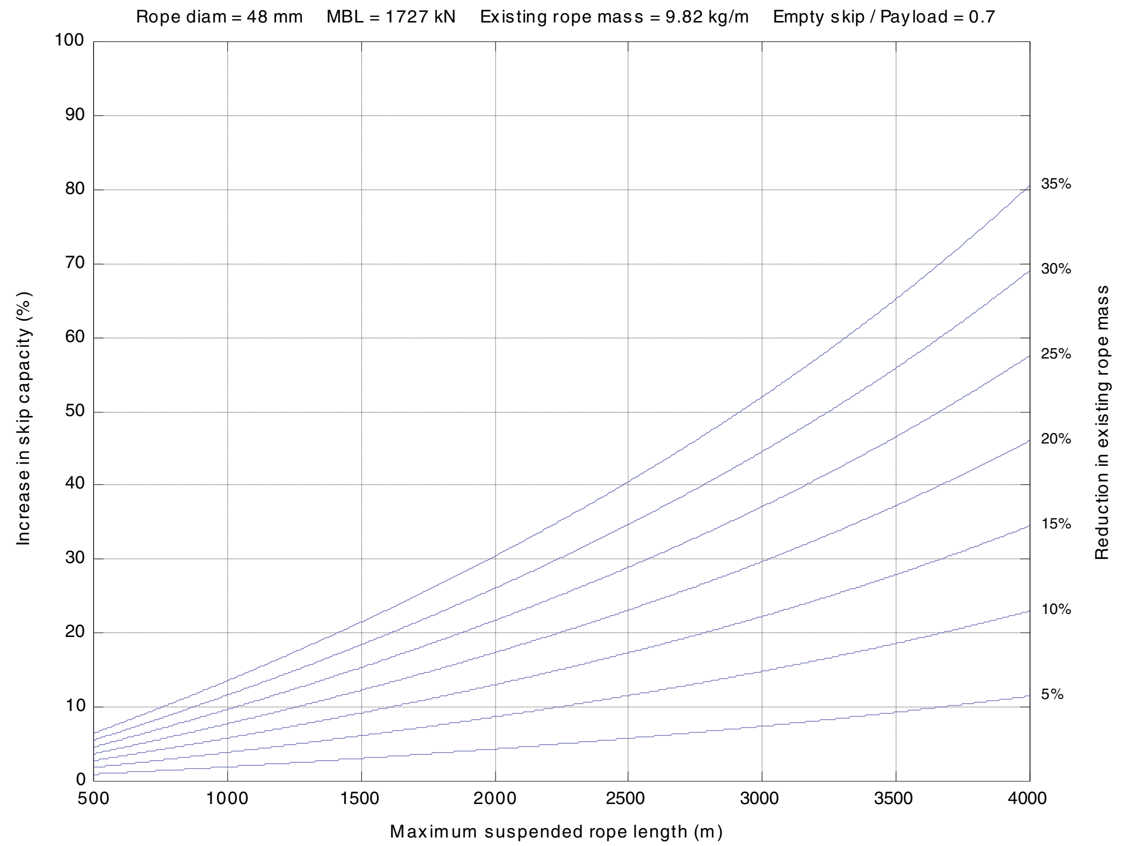

FIG 5 - Influence of rope mass reduction on skip capacity for a typical vertical shaft drum winding installation. For these calculations it was assumed that the rope breaking strength and diameter remain unchanged.

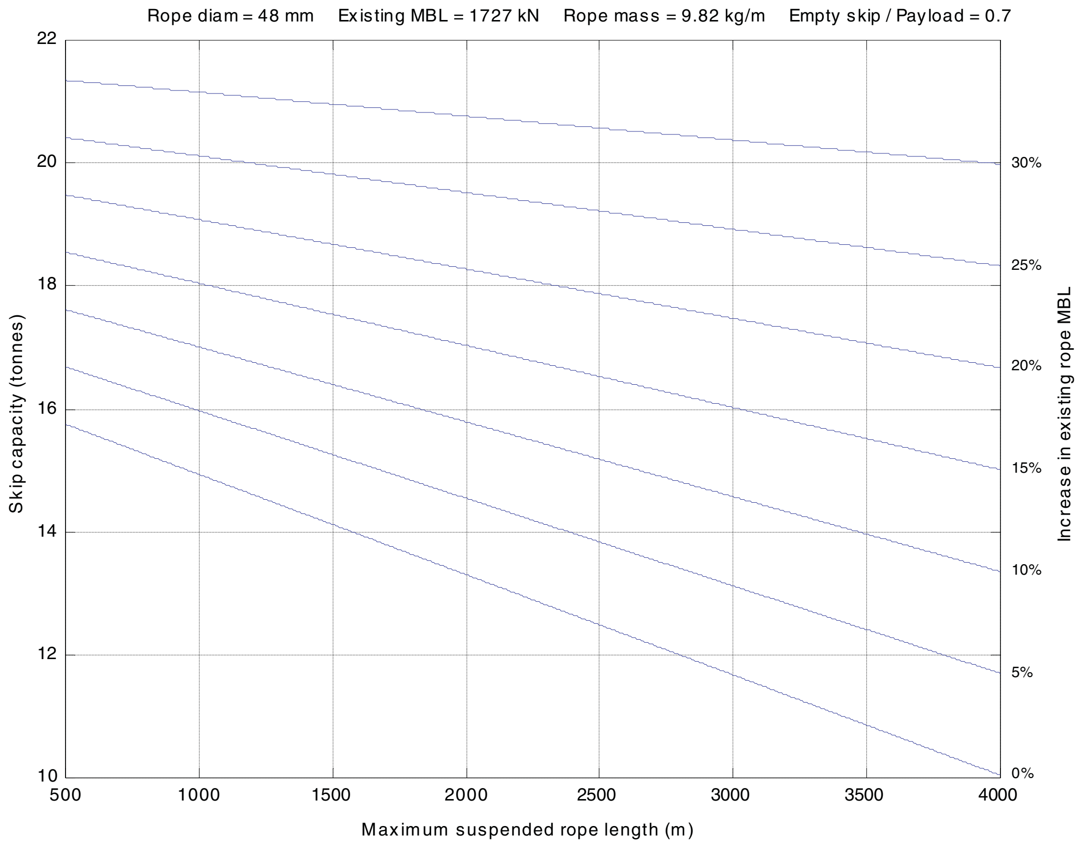

FIG 6 - Calculated skip capacity based on typical mine hoisting system parameters for vertical shaft drum winders. The family of curves show the effect of increases in rope breaking load (*MBL*) on the skip rock capacity, with maintained rope mass per unit length and diameter.

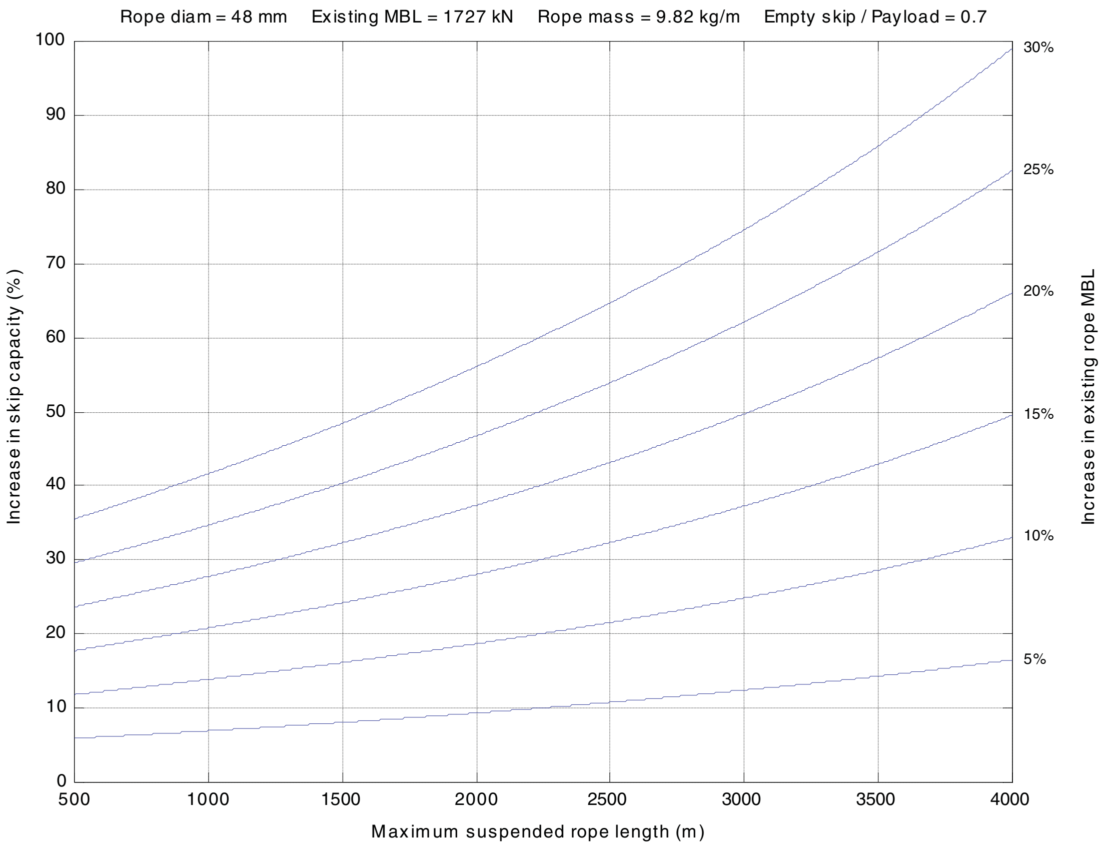

FIG 7 - Influence of rope breaking strength increase on skip capacity for a typical vertical shaft drum winding installation. For these calculations it was assumed that the rope mass per metre and diameter remain unchanged.

The effect of capacity factor on the outcomes of the two possibilities for rope improvement would have different implications to those shown in the earlier figures. Capacity factor limits the factor of safety at the skip and so generally in shafts shallower than 2000 m this is the primary design consideration. In such cases lighter ropes of the same breaking strength and diameter would not hold the same benefits as stronger ropes with the same mass and diameter.

Characteristic lengths

For a particular rope construction, the ratio of the rope breaking strength to the mass per unit length (MBL/ρ) is largely a constant value over the full range of typical diameters used for mining hoisting applications. This value is also the suspended length in metres where the rope would break under its own weight with no attached end load, known as the *characteristic length*. For the 1900 MPa standard mine hoisting ropes considered in the above calculations, the ratio of MBL/ρ is on average 17 900 m (N/(N/m) or kN/9.81*1000/(kg/m)). For a steel rod with a tensile grade of 1900 MPa and density of 7850 kg/m^3 the *characteristic length* would be 24 673 m. In comparison to other engineering materials, high-strength steel wires have relatively low *characteristic lengths*. Materials like Kevlar® and Spectra 1000® show values between 200 and 315 km. When comparing these *characteristic lengths*, it is clear that there should be considerable room for improving the lifting capacity or efficiency of mining ropes. Table 1 shows how *characteristic lengths* differ for a range of materials. This is really a measure of the lifting efficiency of the materials.

CASAR currently manufacture steel wire ropes for drum winding applications with *characteristic lengths* of between 19 700 m and 21 700 m based on the minimum rope breaking strength. New technology developments, some of which are under patent application, will allow for significant increases in lifting performance for mining applications. It is very likely that values of 25 000 m could be achieved in the near future with no negative effects on rope performance in service. The sample calculations in this section have shown that such ropes would have significant benefits for mining companies. The improved rope technology would allow more material to be hoisted from existing shaft installations and result in optimised designs for future deep vertical shafts.

Another benefit of composite ropes – reduced lay length changes

Besides the hoisting capacity advantages that composite ropes would offer, they could also be useful is addressing the problems with lay length changes on deeper shaft drum winders and torsional instability of ropes on Koepe winders. Rebel (1997) studied the torsional behaviour of triangular strand ropes for drum winders in detail and concluded that reductions in rope mass per metre could have a notable effect on the extent of lay length changes in deeper shaft applications. It was recommended at that time that triangular strand rope development should focus on the reduction of rope weight per unit length while maintaining the diameter and breaking strength. Indications were that a ten per cent reduction in weight per unit length could delay lay length changes at installation by 500 m (ie 2500 m lay lengths at 3000 m suspended length). Replacement of metallic components in the rope cross-section with lightweight material such as polymer fibres or extruded polymer profiles was identified as well as the alternative solution of including high-strength aramid type fibres into the cross-section, which would contribute to the rope strength.

A TURBOPLAST COMPOSITE ROPE – APPROXIMATE CALCULATIONS

In the previous section it was demonstrated that a composite rope can enhance hoisting performance compared to a steel-only rope, but can such a rope be made based on existing rope designs? A 48 mm TURBOPLAST rope has a nominal metallic cross-sectional area of 1201.1 mm^2 and a basic structure as shown in Figure 8.

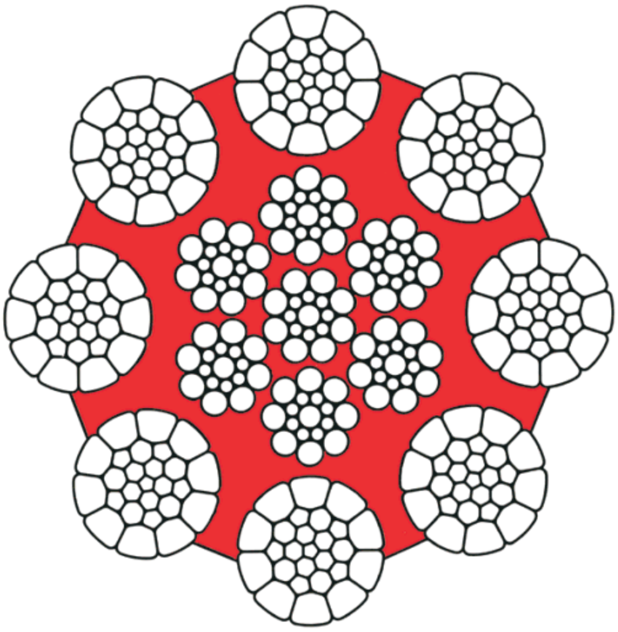

FIG 8 - Cross-section of a TURBOPLAST rope typically used on drum winders and Koepe winders up to suspended lengths of 1000 m.

TABLE 1

Mechanical properties of various materials (note that the values given are meant as an indication only and tend to differ from one reference to another).

Material	Density (kg/m³)	Modulus (GPa)	Tensile strength (MPa)	Characteristic length (km)
Steel wire rope	-	120	-	19
Drawn steel wire	7850	207	1960	25
Carbon fibre	1770	300	3400	196
Technora® fibre	1390	73	3400	249
Kevlar® 49 fibre	1440	125	3600	255
Dynema® SK75 fibre	970	89	2700	284
Spectra® 1000 fibre	970	113	3000	315
Carbon nanotubes	1400	400	50000	3641

The 48 mm TURBOPLAST rope also has the following properties:

Mass	= 10.449 kg/m
Assumed steel density	= 7850 kg/m^3
MBL	= 2018 kN with 1960 MPa steel wire
Characteristic length	= 19 687 m based on the MBL and the mass per metre

As an approximation, based on the metallic cross-sectional area, in each metre of rope there must be 9.429 kg of steel and the remaining 1.020 kg should be made up of the plastic layer and lubricant.

The objective in this analysis is to determine the effect of introducing varying amounts of material of a density of 970 kg/m^3, a modulus of 113 GPa and UTS of 3 GPa (eg Spectra® 1000) on the rope mass per metre and hence *characteristic length* (in m or km).

It is assumed that the fibre material has the same average modulus as the wires formed helically into a rope and so when these are included in line with the axis of the rope they contribute to the share of the rope load in direct proportion to their cross-sectional area, relative to the overall load bearing area of the rope (1201.1 mm^2). This assumption is from simple principles for analysing statically indeterminate structures composed of different materials. The assumption also leads to the conclusion that the nominal tensile stress in the fibres and the steel wires will be similar.

The approximate mass per metre of the composite rope would be:

$$\rho_{rope} = \frac{1201.1 \times \rho_{steel} \times (1 - r_f)}{10^6} + \frac{1201.1 \times \rho_{fibre} \times r_f}{10^6} + 1.02 \text{ (kg/m)} \quad (4)$$

where:

$$r_f = \frac{Fibre\ Area}{Total\ Area}$$

Figures 9 and 10 show the results of calculations based on Equation 4.

In the case of the calculated *characteristic length* it was assumed that the rope minimum breaking strength of 2018 kN remained unchanged by the introduction of the fibre components.

The earlier calculations on the effects of rope mass reduction and strength increase on skip capacity showed that ropes with a *characteristic length* of between 25 km and 27 km would have very significant implications for hoisting efficiency, particularly in deeper shafts. In the case of the new South African static factor of safety, which decreases with an increase in suspended length (25 000/(4000 + *L*)), it has been shown that a rope with a *characteristic length* of 25 km would be able to hoist the same payload irrespective of the depth of the shaft.

The question that arises is what possible rope configurations would produce a fibre area/total area ratio of between 0.25 and 0.35. The last column in Table 2 shows how this ratio varies for different numbers of outer strands in a typical round strand rope construction. It can be seen that ropes with between seven and ten outer strands would satisfy this criterion. Drum winder ropes like the TURBOPLAST construction currently have eight outer strands and so this construction is ideally suited as the starting point for a composite rope design.

It is clear from the preceding analysis that an eight or nine strand TURBOPLAST rope with a high-strength fibre core could achieve the target *characteristic length* of 25 km and 27 km.

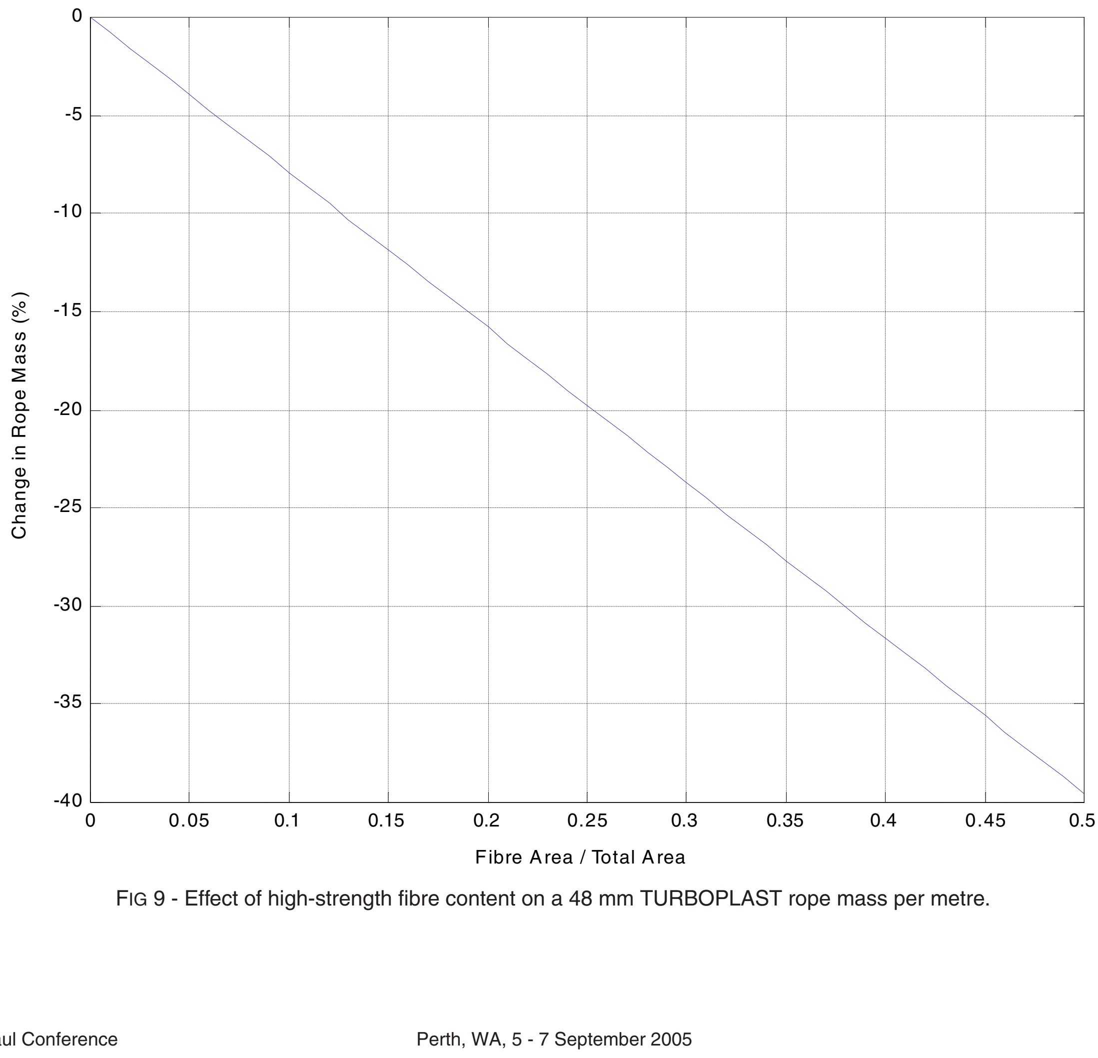

FIG 9 - Effect of high-strength fibre content on a 48 mm TURBOPLAST rope mass per metre.

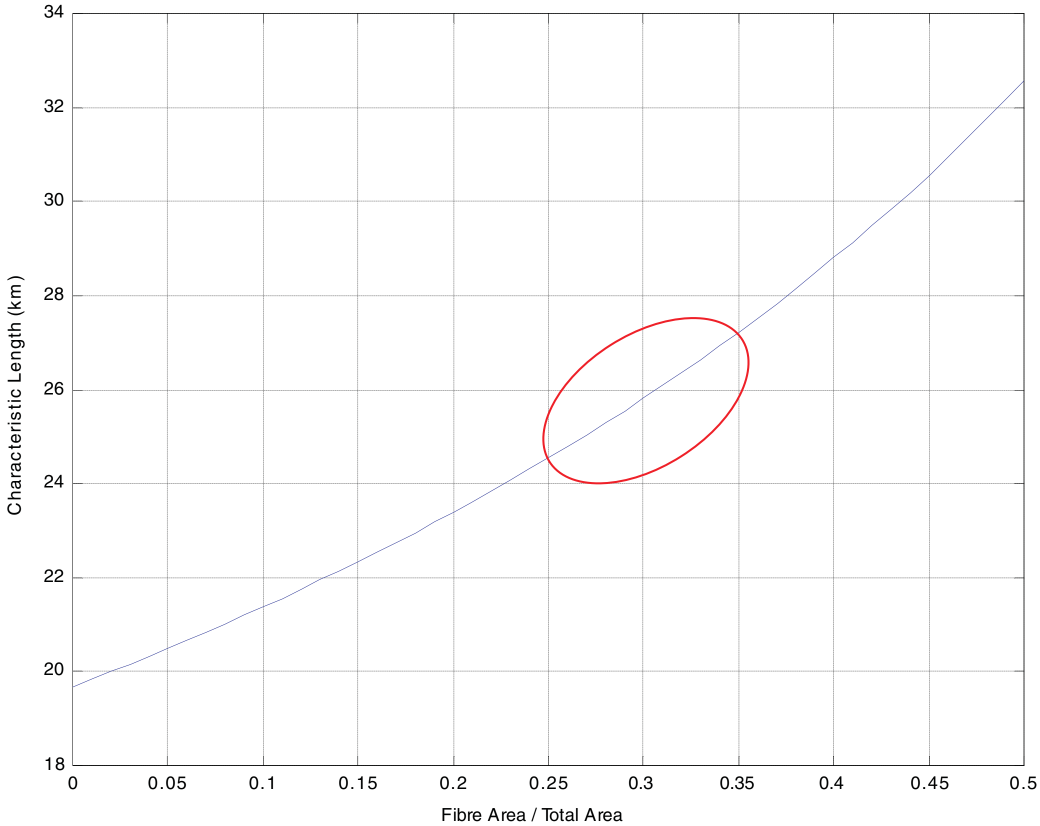

FIG 10 - *Characteristic length* of a 48 mm TURBOPLAST rope for varying amounts of high strength fibre content. The circled area shows the target *characteristic lengths* that need to be reached in order to achieve measurable improvements in shaft hoisting efficiency.

TABLE 2

Rope strand and core load bearing areas for a 10 mm diameter rope. Note that the rope diameter is not critical here but rather the ratio between the outer strand and core areas with regard to the total cross-sectional area.

No of outer strands	Outer strand diameter (mm)	Core diameter (mm)	Section of outer strands compacted fill factor = 0.89 (mm^2)	Section of core fill factor = 0.85 (mm^2)	Total load bearing area (mm^2)	Section of outer strands as percentage of total area (%)	Section of core as percentage of total area (%)
6	3.202	3.595	43.01	8.63	51.64	83.3	16.7
7	2.871	4.257	40.34	12.10	52.44	76.9	23.1
8	2.617	4.766	38.30	15.16	53.46	71.6	28.4
9	2.387	5.226	35.84	18.23	54.08	66.3	33.7
10	2.200	5.600	33.83	20.94	54.77	61.8	38.2
11	2.039	5.922	31.97	23.41	55.38	57.7	42.3
12	1.900	6.200	30.28	25.66	55.94	54.1	45.9
13	1.778	6.444	28.73	27.72	56.45	50.9	49.1
14	1.668	6.664	27.23	29.65	56.87	47.9	52.1
15	1.571	6.858	25.88	31.40	57.28	45.2	54.8
16	1.484	7.032	24.63	33.01	57.64	42.7	57.3
17	1.405	7.190	23.46	34.51	57.97	40.5	59.5
18	1.335	7.330	22.42	35.87	58.29	38.5	61.5

NON-DESTRUCTIVE TESTING ISSUES

A key factor in the design and operation of composite mining ropes will be the safe and reliable non-destructive testing (NDT) of these. Magnetic inspection techniques are normally applied to the NDT of steel wire ropes and these have been established as an accurate means of condition assessment of wire ropes over many years. If the rope structure would incorporate non-metallic load bearing members, like the high-strength aramid and high-modulus polyethylene fibres, then an immediate question from operators will be how to detect deterioration of the fibre core. How important load bearing fibre core condition monitoring is in practice will depend on the proportion of the total rope area that it represents. Table 2 showed that for an eight strand rope the core would be circa 28.4 per cent of the total area where a 12 strand rope would have a core area representing close to 46 per cent of the total. Clearly the significance of core integrity in these two examples would be different.

An approach to addressing the core condition monitoring would be to demonstrate, through extensive laboratory and field trials, that the fibres always outlast the steel wires in bending and tension fatigue conditions (ie when formed into composite ropes) as well as under conditions of multilayer coiling on drums. It is well known that the fatigue properties of high-strength aramid and polyethylene fibres far exceed those of steel wires. It is therefore not unreasonable to expect that in a properly designed composite rope the fibre core could significantly outlast the outer steel wires under all operating conditions. The design of steel strands for deep shaft winding applications is at a relatively advanced stage and these could be used also for the composite rope (eg the TURBOPLAST outer strands). The challenge would be to design a jacketed fibre core that addressed issues such as inter-fibre fretting and transverse loading that could lead to core deterioration. CASAR is developing a number of different fibre core designs to address these problems.

It is highly likely that operators would still require independent verification of core integrity in spite of the fact that it may always outlast the steel outer strands. Rebel *et al* (2000) gave a detailed analysis of various condition monitoring techniques for fibre mooring ropes used in offshore applications (where magnetic techniques can not be applied). Different approaches to condition monitoring were listed including:

- vibrational techniques,
- magnetic resonance,
- conductive internal elements, and
- fibre optics, including:
  - Mach-Zehnder interferometers,
  - Sagnac/Michelson interferometers,
  - Fabry-Perot interferometers,
  - intensity-based sensors,
  - speckle pattern sensors,
  - Brillouin scattering, and
  - intra-core Bragg reflection grating sensors.

Of the methods of non-destructively monitoring fibre ropes the use of fibre optic systems appeared to be the most feasible and there are already specific examples of ongoing development of this technology for fibre ropes and steel strands. The proposed fibre optic techniques rely primarily on the application of distributed strain sensor systems, which are already being used successfully in other 'smart' materials and structures. In the case of ropes, and particularly fibre ropes, relatively high operating strains prevent simple insertion of the monitoring fibres into the structure and so strain attenuation schemes need careful consideration. Figure 11 shows an example of the integration of a fibre optic sensor element into a parallel lay fibre rope.

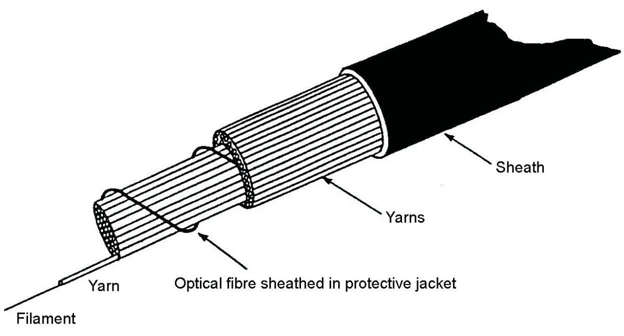

FIG 11 - Structure of a parallel lay fibre rope with an embedded optical fibre sensor (from Robertson and Ludden, 1997).

As part of the composite rope development program, CASAR is addressing the NDT issue and the practical solution to this problem will form part of the composite mining rope product offering.

FUTURE DEVELOPMENTS

In the last five years material science researchers worldwide have been investigating the mechanical properties of carbon nanotubes (CNTs), which were discovered in 1991 by the Japanese electron microscopist Sumio Iijima. CNT fibres are likely to give tensile strengths in the range 50 GPa to 100 GPa with a modulus considerably higher than drawn steel wire (ie greater than 207 GPa) and a density of around 1400 kg/m³. This would result in *characteristic lengths* in excess of 3600 km compared to 25 km for steel wire and circa 19 km for steel wire rope (see Table 1). Universities like Cambridge in the UK and MIT and Rice in the USA are working actively on techniques to grow carbon nanotubes on a continuous basis to form the lengths that would be necessary for serious lifting applications like mine hoisting. The mechanical properties of CNTs are so superior that they have even been proposed for use in the space elevator being explored by the NASA Institute for Advanced Concepts (NIAC). The NIAC Phase 1 report by Edwards and Westling (2003) gives this basic description of the concept:

> *The simplest explanation of the space elevator is that it is a ribbon with one end attached to the Earth's surface and the other end in space substantially beyond geosynchronous orbit (100 000 km altitude). The competing forces of gravity at the lower end, and outward centripetal acceleration at the farther end, keep the ribbon under tension and stationary over a single position on Earth. This ribbon, once deployed, can be ascended by mechanical means to Earth orbit.*

This is clearly a far more complicated problem than mine hoisting from 3000 m or 4000 m below surface. However, if CNTs show such promise to allow for applications like the space elevator then it is quite likely that they could also revolutionise mine winding rope technology.

Even if the CNT fibres become commercially available in the next five to ten years it is still foreseen that these could only be used as core material in a steel wire rope as the steel will still be required on the outside to protect the mechanically more fragile core. At present the immediate advantage of CNTs would be that their modulus is significantly higher than existing high-strength aramid fibres and polyethylene fibres. Modulus matching between the different helical elements in a composite rope is important to ensure equal load sharing. However, it is not impossible that as CNT synthesis improves, hoisting ropes could be developed where the entire rope load is carried by the fibre core and the steel wires on the outside are purely used for mechanical protection. This would be fundamentally different to the ideas already discussed in this paper where the outer steel wires are still seen as the primary load-bearing elements. Such changes in rope design would need to clearly address the above-mentioned NDT issue as part of the development program.

CONCLUSIONS

The analysis in this paper has shown that composite mining ropes can significantly enhance the performance of deep shaft hoisting systems by allowing for notable reductions in rope mass per metre while maintaining rope diameter and breaking strength. For future deep shafts the implications of changing to composite ropes are so dramatic that their use could change the economics of a shaft hoisting system. This could take new development projects from not feasible to feasible, allowing greater flexibility to mining companies in their investment decision making. The application of composite ropes in existing shafts could allow greater payloads to be hoisted with the same winding plant. For rock winders this would lead to increases in shaft output and greater returns on existing capital investment. CASAR have an active program for developing composite mining ropes and the delivery of such technology will be a key driver for company growth in the future. The company is interested in partnering with mining companies worldwide to ensure that the new rope designs are practical and that they address customer requirements in terms of specifications and operational performance.

REFERENCES

Dolan, T G, 2003. Carbon fibres for the wire rope industry? *Wire Rope News and Sling Technology*, 25(2):8,11-13.

Edwards, B C and Westling, E A 2003. *The Space Elevator: A Revolutionary Earth-to-Space Transportation System*, 288 p (Spageo Inc: San Francisco).

Hearle, J W S, O'Hear, N and McKenna, H A, 2004. *Handbook of Fibre Rope Technology*, 416 p (CRC Press: London).

Klees, D A, Hoganson, R B and Data, H L (AMSTED Industries Inc), 1989. Rope with fibre core and method of forming same, US Patent 4887422.

McKenzie, I D (Haggie Rand Limited), 1990. Reduced mass rope, South African Provisional Patent Application No 89/8857.

Olsen, E G and O'Donnell, H J (Otis Elevator Company), 1999. Apparatus to inspect hoisting ropes, US Patent 5890564.

Rebel, G, 1997. The torsional behaviour of triangular strand steel wire ropes for drum winders, PhD thesis, University of the Witwatersrand, South Africa, 328 p.

Rebel, G, Chaplin, C R, Groves-Kirkby, C and Ridge, I M L, 2000. Condition monitoring techniques for fibre mooring ropes, *Insight – Journal of the British Institute of Non-Destructive Testing*, 42(6).

Robertson, P A and Ludden, B P, 1997. A fibre optic distributed sensor system for condition monitoring of synthetic ropes, *IEE Colloquium (Digest)*, 033:12/1-12/6.

SANS, 2000. SANS 10294, Edition 1: The performance, operation, testing and maintenance of drum winders relating to rope safety, South African National Standards, Pretoria, pp 1-43. Rope factor of safety equation included from Regulation 16.34.2 of the South African Mine Health and Safety Act, 1996 (Act 29 of 1996).