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High strength fibre cored steel wire rope for deep hoisting applications

Summary

The concept of combining high strength fibre with steel to make lightweight ropes for deep shaft hoisting applications is not new. However, until now development of serviceable ropes has been hindered by technological feasibility.

This paper reports on the progress in the development of such ropes being made as a joint project between fibre and steel wire rope manufacturers. An important objective in the design of such a "composite" rope is to ensure that fibre and steel elements take a proportional share of the load so that both fibre and steel components are used to their full potential.

With these issues in mind, composite ropes have been designed and manufactured. Results are presented for initial strength measurements on ropes which show that a previously unattained strength to mass ratio is achievable. Some preliminary fatigue data is also included. Finally the authors discuss the further work needed before these ropes may be employed in winder installations.

1 Introduction

1.1 The concept of high strength light weight ropes

Previously, authors such as Dolan [**1**] have discussed how high strength carbon fibres can be used to enhance the properties of wire ropes in applications where special mechanical properties are needed that are not provided by steel–only constructions. There is also a substantial body of literature which deals with the application of high strength fibre ropes (i.e. fibre only) in various applications such as elevator systems and offshore mooring. Examples include the book by McKenna *et al.* [**2**] which gives a broad description of the design and application of fibre ropes and Olsen and O'Donnell [**3**] where the use and magnetic inspection of Kevlar® elevator ropes is described. O'Hear *et al.* [**4**] discuss the use of synthetic fibre ropes for mine winding.

However, for lifting applications fibre–only ropes may not be robust enough to withstand handling during installation and maintenance operations. Deterioration on multi-layer drums will also be a limiting factor. The solution to the problem would seem to lie between the two: composite steel–fibre ropes which would combine the robustness of a steel rope with the weight saving properties of fibre ropes.

This paper is concerned with the development of such composite ropes for lifting applications, some of the background concept of which has been previously reported by Rebel *et al.* [**5**]. The term "composite" is taken to mean a rope which is a steel–

fibre combination rope where the fibre in the rope is an integral load bearing member, rather than just acting as a support for the outer strands. The type of fibres under consideration here are of the aramid type (e.g. Twaron®, Technora® (an aramid copolymer) or Kevlar®) which have a very high breaking strength associated with low stretch and low densities (compared with steel) as well as dimensional stability over a wide temperature range. Table 1 summarises the properties of several available aramid fibre types, along with those of steel wire such as would be used in a rope for comparison.

Fibre Type	**Strength (MPa or N/mm^2)**	**Elongation at failure (%)**	**E-Modulus (GPa)**	**Density (g/cm^3)**
Standard modulus (SM) aramid	3250	3.7	75	1.44
High modulus (HM) aramid	3100	2.7	105	1.45
Copolymer aramid	3410	4.4	74	1.39
Rope wire (highly drawn steel)	1770	2.6	200	7.85

Table 1: Examples of the properties of high strength aramid fibres, as well as (for comparison) typical properties for steel rope wire.

The idea of combining high strength fibres with steel wires in a rope construction has been previously considered. 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 [**6**]. Several years later Klees *et al.* [**7**] described a composite steel wire rope in their US patent which is similar to the configuration discussed here, but with some significant differences. Figure 1 shows the cross-section of the Klees *et al.* rope structure which includes a jacketed Kevlar® core. Klees *et al.* note of the 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”.

An extension to the idea of the composite rope is the tapered mass rope proposed by McKenzie [**8**] with the application of deep mine (drum winder) hoisting in mind. The tapered mass rope involves progressively removing steel from the rope to reduce its mass (and breaking strength) while maintaining the overall rope diameter. The motivation for this design is that in deep vertical shafts less rope strength is required at the conveyance “end” 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-section 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 *et al.* and others, is a more realistic solution for a light weight rope.

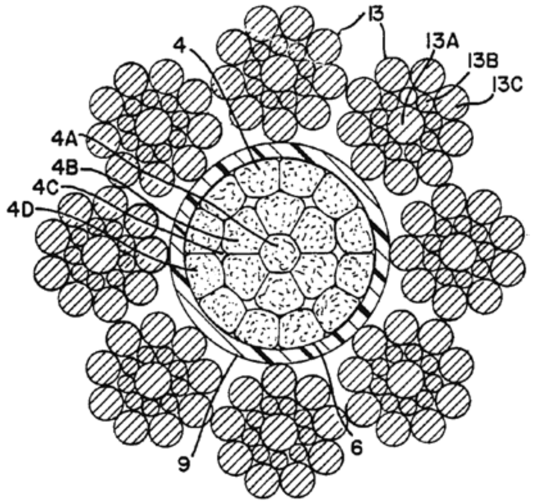


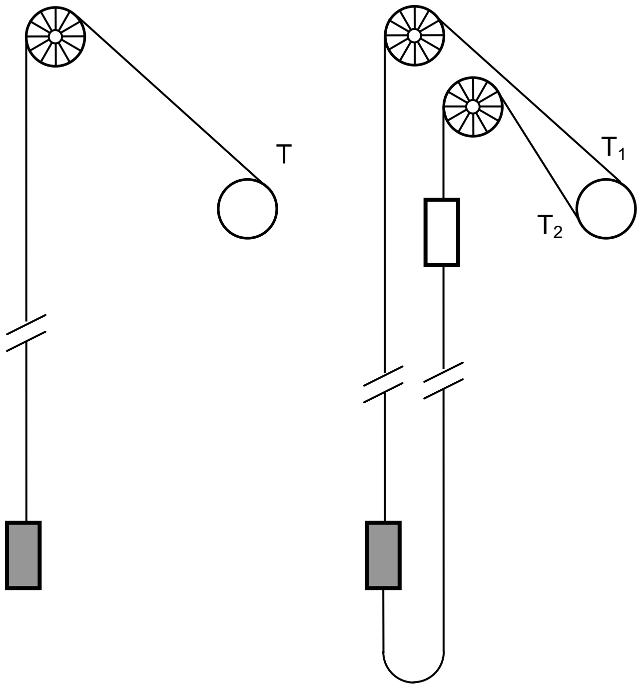
Figure 1: Composite steel wire rope as proposed by Klees et al. [**7**] in their US patent filed in September 1988. 4 - Kevlar® core and core elements, 6 - Lang's lay coated fibre core, 9 - Core protective coating, 13 - Steel outer strands.

1.2 Winder installations

The two main classes of winder in operation in the mining industry are the drum winder and the Koepe (friction) winder (Figure 2). In the case of the drum winder, Figure 2a, the benefits of using either a light weight rope or a stronger rope of the same diameter have been explored previously by Rebel *et al.* [**5**]. The tension T supported by the rope is a result of the weight of the suspended rope and the skip/payload. By reducing the linear rope mass (but retaining the rope strength), it is straightforward to see the opportunity for an increase in the skip/payload whilst keeping all other winder parameters the same. The maximum tension T will be unaffected by whether the load comes from the skip/payload or from the self weight of the rope. Thus there is a direct correlation between saving weight in a hoisting rope and improved haulage capacity (Figure 3).

The advantages of using a light weight rope in a Koepe installation (Figure 2b) are not so directly apparent. The design of a Koepe winder incorporates tail ropes which are employed specifically to compensate for the different total rope weights either side of the drum caused by the moving lengths of the head ropes as they hoist or lower the skips. Thus the tensions T_1 and T_2 and more specifically the ratio T_1/T_2 deals primarily with the imbalance between payload in the full and empty skips, and to a lesser extent the rope. If a lightweight rope is employed in a Koepe system which remains otherwise the same (i.e. if used on an existing installation), the benefit will be that a lower rope mass will reduce the cyclic fatigue stress range experienced.

Another advantage of reducing rope mass (in both Koepe and drum winders) is that it leads to smaller torsional deformations for a given depth [**9**].



(a) Drum winder (b) Koepe winders: ground mounted (l), tower mounted (r)

Figure 2: Schematic diagram showing the principles of operation of drum and Koepe winders.

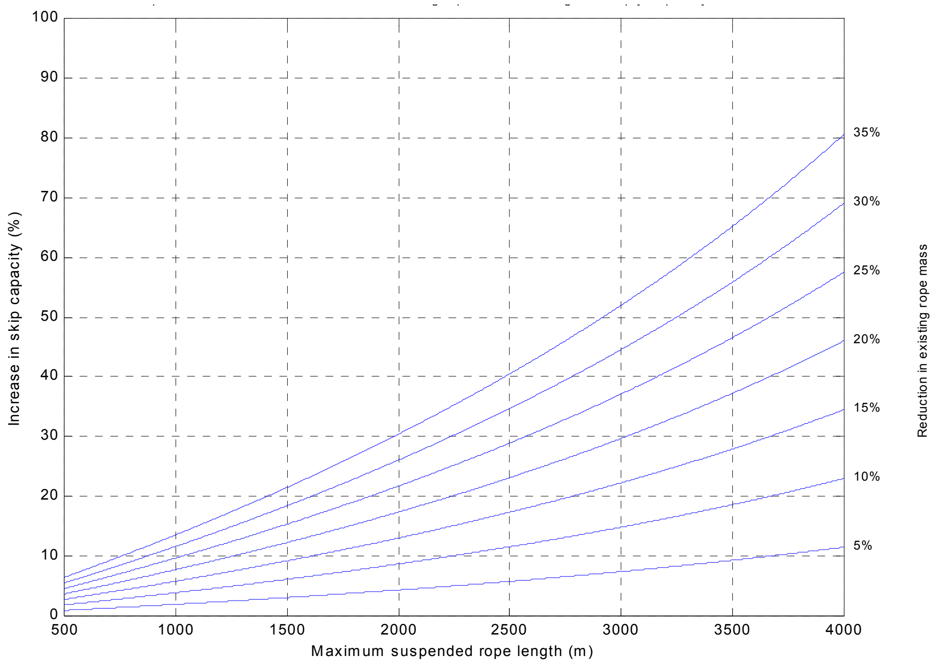


Figure 3: Influence of rope mass reduction on skip capacity for a typical vertical shaft drum winding installation. For these calculations it was assumed that the rope breaking strength and diameter remain unchanged (from [**5**]).

In the case of the Koepe winder, Figure 4 shows how significant benefits in terms of payload may be gained if it is viable to increase the T_1/T_2 ratio. It is noted, however, that care has to be taken to avoid rope slip, and consideration must also be given to the power requirements needed to accelerate the out of balance forces $T_1 - T_2$. For the composite rope which will be described here, a typical reduction in rope mass of 20% may be obtained. It can be seen that at depths beyond approximately 1,500 m that the potential increase in skip capacity becomes appreciable.

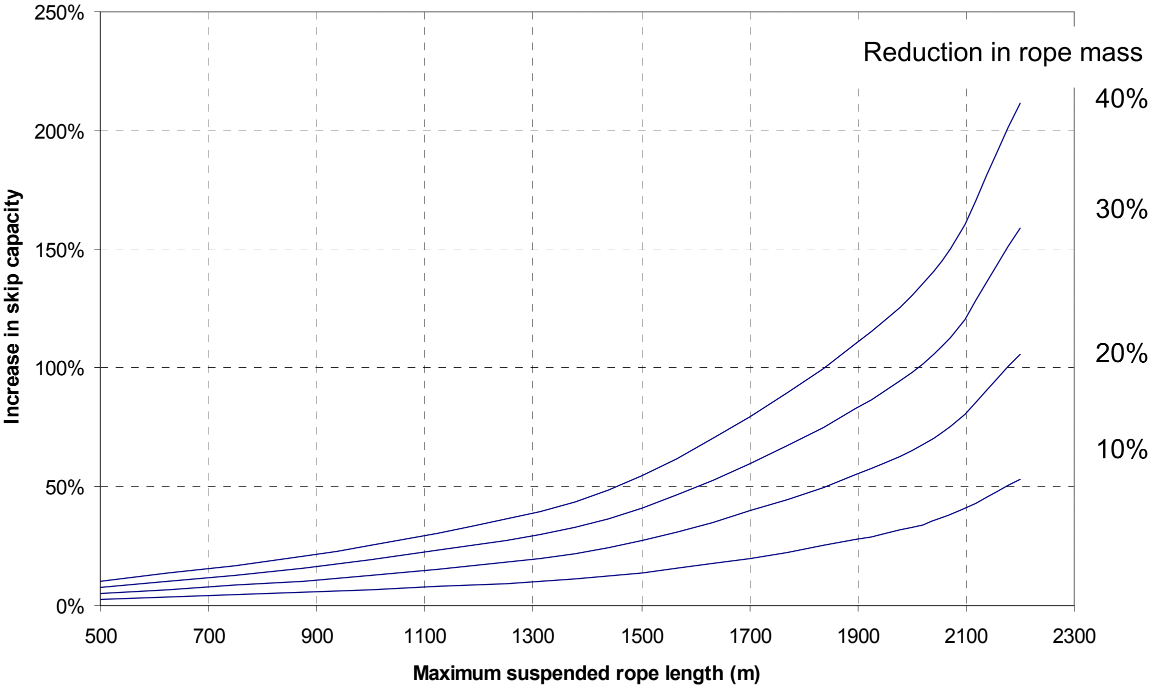
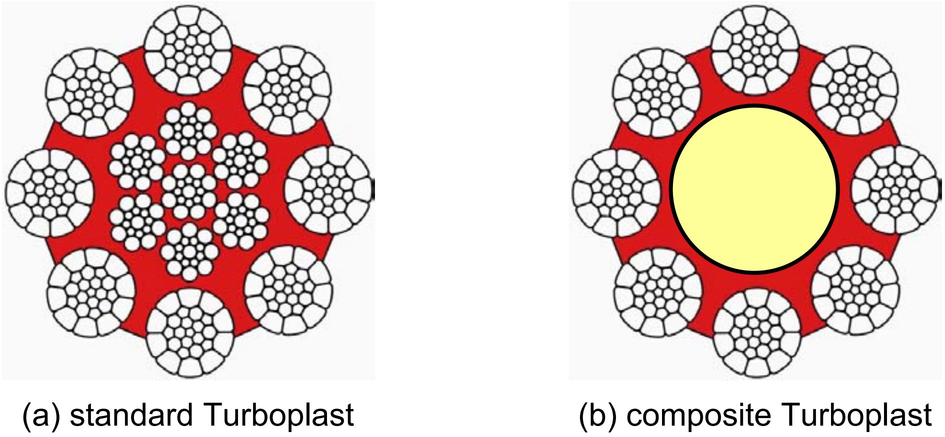


Figure 4: Influence of rope mass reduction on skip capacity for a typical Koepe winding installation (6 head ropes of Ø50 mm, 1770 MPa, FoS 6.5). For these calculations it is assumed that the various ropes' breaking strength and diameter remain unchanged.

2 Rope design

A Turboplast wire rope construction (Figure 5a) was chosen as the basis for the present composite rope development. The standard "all steel" version of this rope has been successfully employed in mining applications where the good flexibility of an eight strand rope is combined with high wear resistance from compacted outer strands. The plastification (represented in red in Figure 5) is also a major benefit in enhancing the performance of the rope, acting as a cushion and support between the strands themselves and core and strands. An eight strand rope is also ideal for a composite rope design, as the metallic cross sectional area of the core is approximately 25% of the whole rope, which is sufficient to demonstrate the benefit of the inclusion of a high-strength light-weight fibre, Figure 5b, [**5**].



(a) standard Turboplast (b) composite Turboplast

Figure 5: Cross sections of the standard Turboplast and composite Turboplast rope constructions.

Initial work has been undertaken on relatively small size ropes. Figure 6 shows the load-elongation for a Ø16 mm standard (steel) Turboplast rope taken to failure. It can be seen that the relationship is very non-linear and that there is a high elongation of the structure at failure (in this case just over 4%).

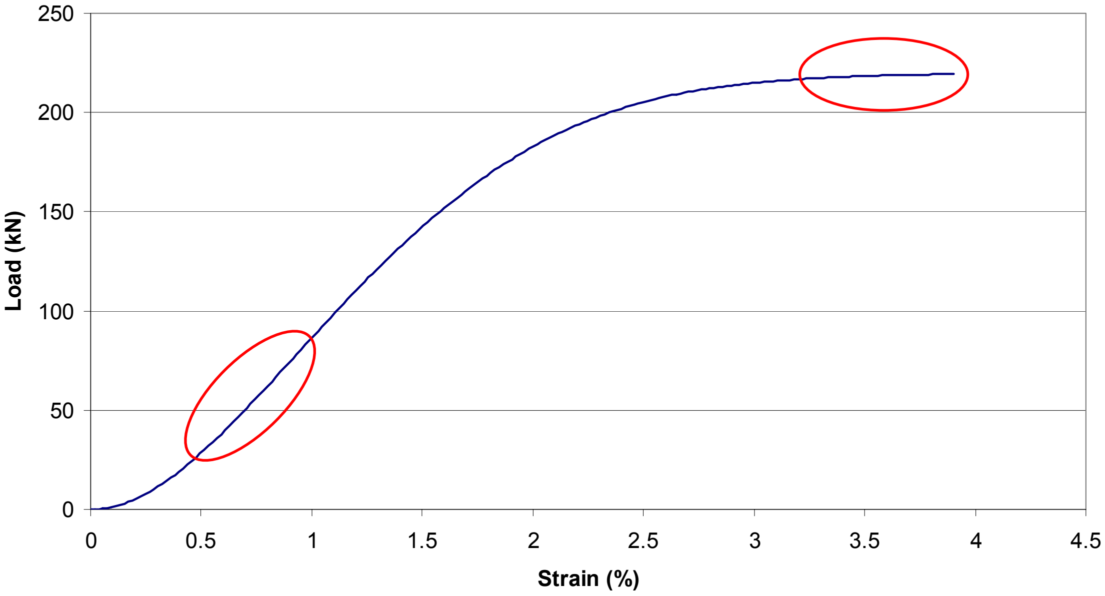


Figure 6: Load-elongation characteristics for a standard (steel) Turboplast rope (Ø16 mm 1770 grade zZ galvanised). The areas marked in red indicate the typical loads at which good load sharing is important for a composite rope.

The main design criterion when developing the fibre core is to match the standard rope load-elongation characteristics and to ensure that there is good load sharing between fibre and steel particularly at the rope's *operational* loads.

However, it must also be noted that rope systems are designed and ropes sold according to the rope (ultimate) breaking strength (F_{UBL}) (or more usually the manufacturer's minimum breaking load (F_{min}) which is a few percent below F_{UBL}). So, although in practice the rope will not operate at load levels anywhere near the breaking load, it is also very desirable to obtain a breaking strength at least that of the F_{min} of the standard steel rope. Thus, design of a fibre core for a composite rope will need to take into account the characteristics both at the working load of the rope and also at loads approaching the breaking strength.

The fibre core for the composite rope was designed using conventional rope geometry. For use in the composite rope a braiding was incorporated on the fibre core in addition to the plastification of the rope. The braiding provided structural integrity of the core rope during handling/manufacture and additionally protected it from dirt or particle ingress which could cause accelerated wear during service. A further benefit was to protect the fibre rope from plastic ingress during the plastification process which again would cause accelerated wear on the fibres during service. The plastic impregnation of the rope provides a cushioning effect and improved load sharing between the strands and the core.

3 Preliminary testing

Two core ropes were designed for the first composite ropes using Twaron® aramid fibre material, one of standard modulus (SM) material (approximately 75 GPa) and the other high modulus (HM) material (approximately 105 GPa). It was decided to use a stranded type rope construction as this would provide a core rope which had good structural integrity and was suitable for further handling. These fibre cores were then closed into Turboplast ropes of finished nominal diameter Ø23 mm. All ropes were manufactured and tested at CASAR Drahtseilwerk Saar GmbH, Germany.

3.1 Stiffness and strength

Measurement was made of the Young's modulus and the breaking strength for both the fibre cores and the complete ropes. The fibre ropes had spliced eye loops at either end of a 6 m sample, and the load-elongation characteristics were measured over a 2 m gauge length. In the case of the complete standard and composite ropes, conventional resin socket type terminations were employed on an 8 m sample. It is noted that by using this method to measure the Young's modulus of ropes, that there will be some influence of socket draw ("setting" of the termination). However, for the diameter of ropes involved, a sample length of 8 m is thought to be sufficiently long to have a negligible effect (e.g. for a 16 mm rope 8 m is 500 rope diameters).

3.2 Fatigue

Following the experience and very promising results obtained with the first pair of ropes described above, additional ropes were designed with the aim to further improve the load sharing between the fibre and steel elements of the rope. Three Ø16 mm composite ropes were designed using different aramid fibres for the core: Twaron® SM, Twaron® HM and Technora®. Technora® was included in the trials as although it has similar properties to SM fibre, it has in addition, excellent fatigue resistant properties.

The opportunity was also taken to manufacture a standard Turboplast rope from which to make comparative tests. Thus, the strands were made with the same wire stock on the same machine in consecutive production runs, so as to give as good a basis for comparison of the behaviour of the ropes as possible.

The fatigue results reported in this paper will compare the performance of the standard Turboplast construction with the HM fibre cored Turboplast rope (Turboplast HM). Results for the SM and Technora® fibre ropes are not available at time of writing.

3.2.1 Tension-Tension fatigue performance

Three pairs of tensile fatigue tests were planned to be undertaken on both the standard and HM ropes. The tests were undertaken with the mine hoisting application in mind and thus all had the same minimum load of 2% F_{min} (this figure may be a little low for typical service conditions) and maximum loads of 16, 20 and 24% F_{min} (a typical static Factor of Safety (FoS) employed by the mines is in the range 4.5 - 6.5, which translates to a maximum static load of 22.2% to 15.4%). The results of these tests are presented in section 4.2.1.

3.2.2 Bending over sheave performance

The basic arrangement of the bending over sheave (BoS) fatigue test equipment is shown in Figure 7. The rope sample is wrapped around the two sheaves in a complete loop, and secured on the larger, top sheave. Tension is applied to the rope by means of a dead load which acts through the axle of the lower (test) sheave. The cyclic bending motion is produced by oscillation of the upper sheave. Figure 7 also shows the various zones in the test rope which will be subjected to different levels of bending. During each machine bending cycle a section of rope will run onto the test sheave and off at the other side (and then back again). This area is termed the double bend region (section BC) as it experiences two full bending cycles for each complete oscillation of the upper driving sheave. Either side of the area of double bending are lengths which experience only one bending cycle per machine cycle (AB and CD). Sections EF and GH will undergo single bending over the top drive sheave under the same test load, but at a much greater D/d ratio. Finally sections DE and AH will remain straight throughout the test.

Inspection of the failed rope sample in the different areas of bending can provide useful information about the behaviour of the rope in fatigue. The length which was located on the drive sheave during testing is also important, as it can give an indication of the performance of the rope operating at much greater D/d ratios such as might be found in a mine hoisting application (in this case D/d = 85, although it is noted that the drive “sheave” is actually a plain drum).

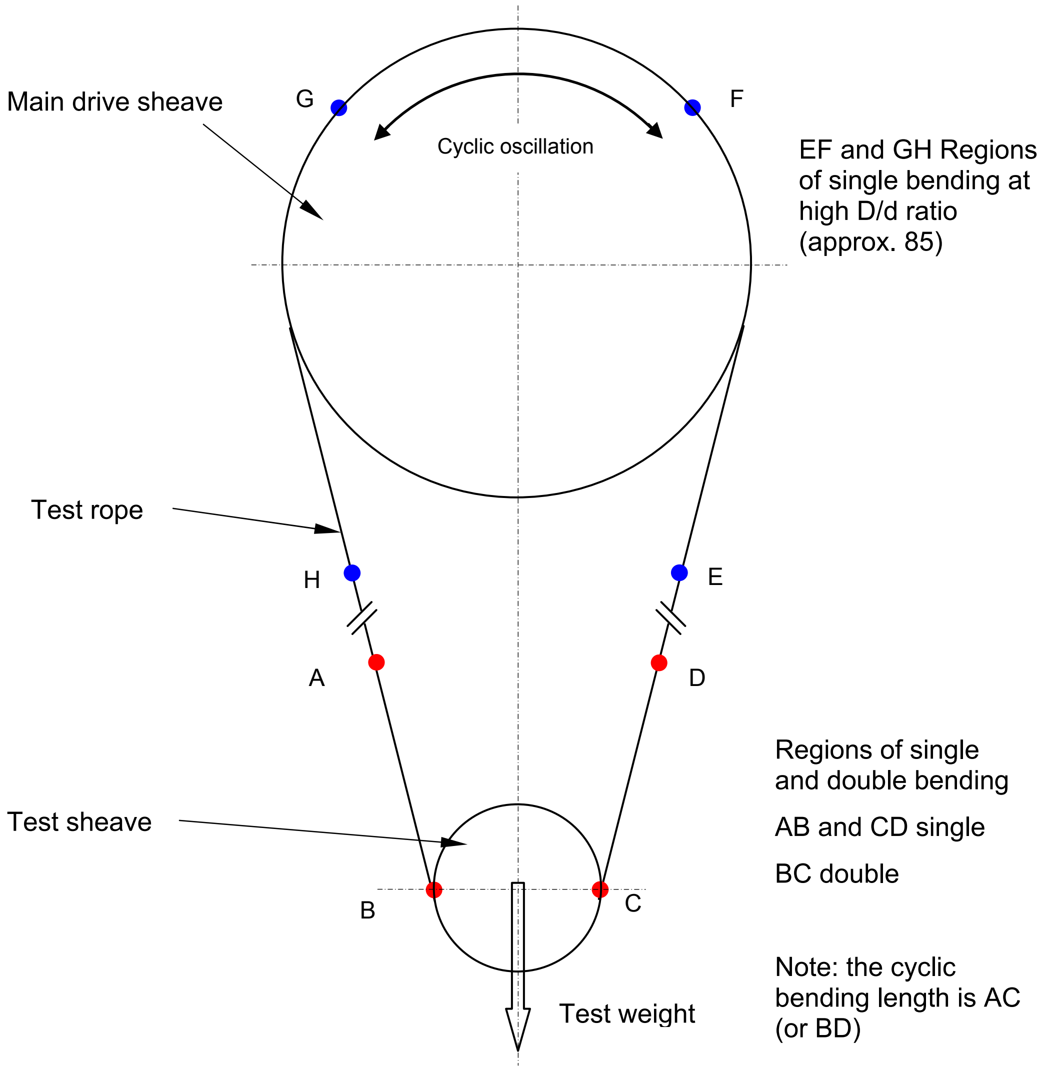


Figure 7: Schematic drawing of the bending over sheave test machine, showing the different regions of bending.

4 Results

4.1 Stiffness and strength

Figure 8 presents results for the tests undertaken on the Ø23 mm standard and HM composite ropes. In both cases the plot shows the load-strain relationship for the complete ropes as well as for their cores. The match in behaviour between the HM fibre core and the standard steel core is very pleasing. This level of match is reflected in the performance of the complete ropes.

It is noted that the elongation at failure for the composite rope is lower than that of the standard Turboplast rope, but the contributions of the core and strand elements at this load are sufficient that the breaking load achieved is in excess of the target F_{min}, and in this case, is greater than the standard rope (Table 2). Table 2 also summarises the results obtained for the composite rope with the SM fibre core.

Table 3 summarises the reduction in rope mass (from standard) and strength to mass ratio for the composite ropes and compares them with a standard rope. Referring to Figures 3 and 4, the reduction in mass value gives an indication of the % increase in skip capacity which would be feasible with these ropes. Note that Figures 3 and 4 assume the same F_{UBL} and so deal with just the mass ratios. Considering the strength to mass ratio (so making use of the added strength), it can be seen that an average improvement of approx. 24% has been obtained.

Tables 4 and 5 summarise the same characteristics for the Ø16 mm ropes.

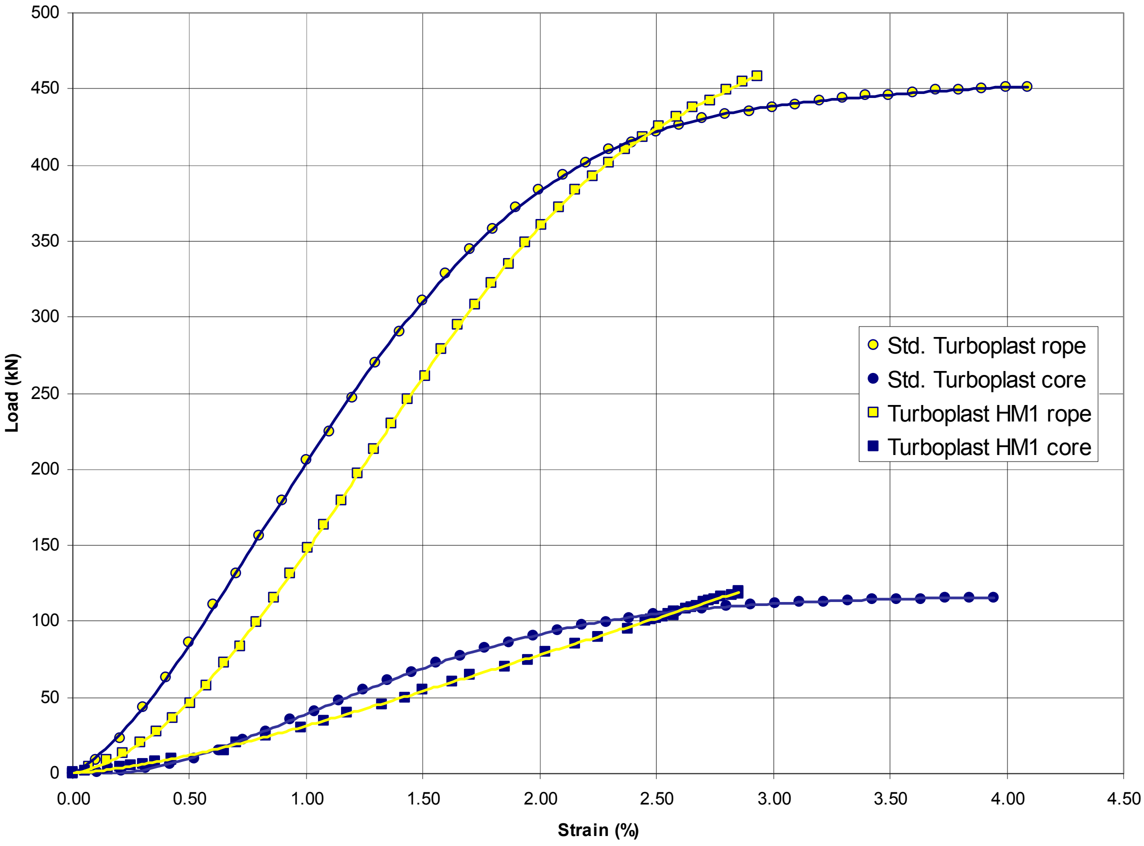


Figure 8: Load-strain characteristics for the Ø23 mm standard (std.) Turboplast rope and core and composite (Turboplast HM) rope and HM core.

Rope	Breaking load (kN)	Breaking load (% F_{min})	E-modulus (GPa)	Elongation at failure (%)
Standard Turboplast	450.6	107.95	112.0	4.09
Turboplast SM	446.0	106.86	93.94	3.28
Turboplast HM	456.6	109.38	99.53	2.93

Table 2: Summary of stiffness and strength results for the Ø23 mm standard and composite ropes.

Rope	Mass per unit length (kg/m)	Reduction in rope mass (%)	Strength (kN)	Strength : Mass (kN/kg/m)	Increase on standard (%)
Std. Turboplast	2.40	-	450.6	188.3	-
Turboplast SM	1.94	**+19.1**	446.6	230.8	**+22.6**
Turboplast HM	1.94	**+19.1**	456.6	235.2	**+24.9**

Table 3: Comparison of the rope mass and strength : mass ratio for the Ø23 mm standard and composite ropes.

Rope	Breaking load (kN)	Breaking load (% F_{min})	E-modulus (GPa)	Elongation at failure (%)
Standard Turboplast	220.7	108.66	112.1	3.97
“	220.7	108.66	111.8	3.90
Turboplast HM	212.7	102.55	94.6	2.55
“	210.5	102.43	97.2	2.43

Table 4: Summary of stiffness and strength results for the Ø16 mm standard and composite ropes.

Rope	Mass per unit length (kg/m)	Reduction in rope mass (%)	Strength (average) (kN)	Strength : Mass (S:M) (kN/kg/m)	Increase on standard S:M (%)
Std. Turboplast	1.173	-	220.7	188.2	-
Turboplast HM	0.940	**+19.8**	211.6	225.1	**+19.6**

Table 5: Comparison of the rope mass and strength : mass ratio for the Ø16 mm standard and composite ropes.

4.2 Results of the fatigue testing

4.2.1 Tension-Tension fatigue performance

Figure 9 presents the initial results obtained in the tensile fatigue tests on the Ø16 mm ropes. Considering first the results for the standard Turboplast, it can be seen that the tensile fatigue behaviour is very sensitive to the load range (maximum load). This sort of characteristic has been noted before by Ridge [**10**] for small diameter (Ø13 mm) standard six strand ropes (non-plasticated and non-compacted) and is thought to be related to the additional drawing stages which the relatively small diameter wires employed in this size of rope undergo during their manufacture. Thus, this characteristic is not necessarily representative of larger diameter ropes of the same construction.

It is also noted that the minimum load used during the tests of 2% F_{min} is fairly low and that there may be some deleterious influence on the fatigue behaviour owing to the increased fretting amplitude of the wires in the rope operating down at this load. Thus whilst the results may be used as a comparison of the tensile fatigue endurance for the two Ø16 mm ropes reported here, they should not be taken as indicative of behaviour for larger diameter ropes.

At time of writing, only one tensile fatigue test has been run on the Turboplast HM rope. The fatigue performance is an order of magnitude better than that of the standard Turboplast. Whilst pleasing, it must be remembered that this is a single test, and more results must be obtained before any firm conclusions can be drawn.

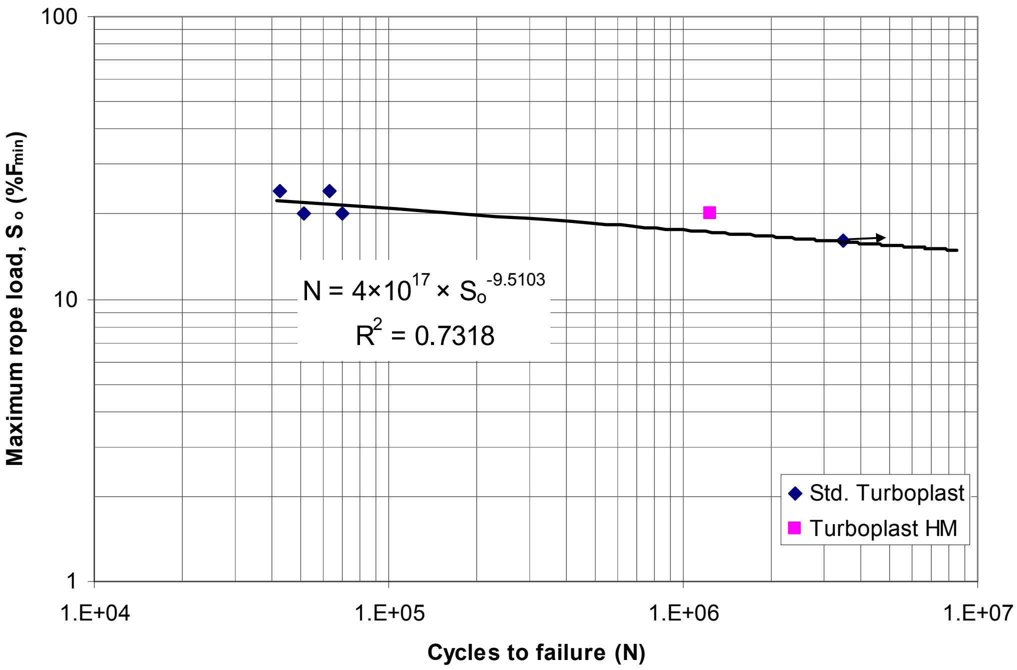


Figure 9: Comparison of the behaviour of the Ø16 mm standard and Turboplast HM ropes in tension-tension fatigue as a function of varying maximum load (with constant minimum load of 2% F_{min}).

4.2.2 Bending over sheave performance

As with the tensile fatigue tests, at time of writing, only limited bending fatigue tests have been undertaken (Table 6). However, the preliminary results are again very promising. In the mine hoisting application D/d ratios may lie anywhere in the range 80 – 120:1, but will be typically 100:1. The tests undertaken so far have been at D/d ratios of 20 and 30, which are much lower and harsher levels than would typically be experienced in service. The results indicate that, as expected, the fibre core in the composite rope is sensitive to the relatively low D/d ratios. In the D/d = 20 test the endurance is about 80% of the standard Turboplast (although it must be noted that the standard Turboplast is an exceptionally durable steel wire rope). However, even in this case, the composite rope still achieves double that predicted for a standard eight strand rope with IWRC (independent wire rope core) [**11**]. At D/d = 30, the Turboplast HM endurance is significantly better than both the standard Turboplast rope and the prediction for the standard eight strand rope.

It is recognised that in the drum hoisting application whilst operating with D/d ratios of 100:1, that locally at the LeBus or coil cross-overs the D/d will be much lower, and probably nearer to the 20 or 30:1 ratios tested here (so these results are additionally useful in informing that aspect of operation). As with all drum winders, the areas of cross over must be monitored, and an effective back-ending policy employed to move the areas of local damage before they compromise the integrity of the rope.

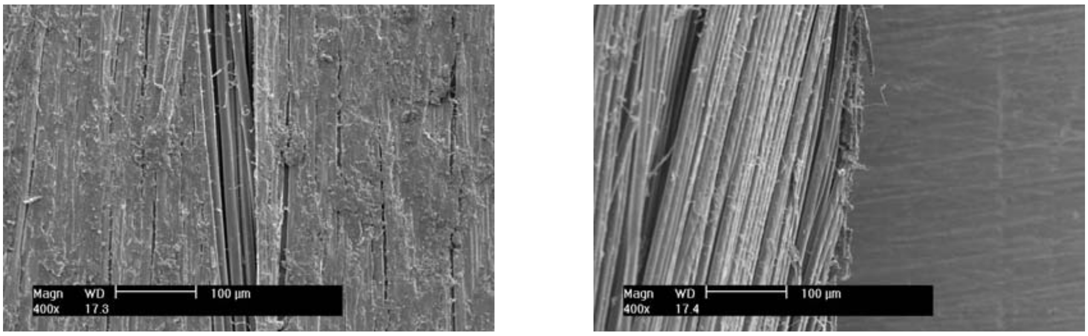
As mentioned in section 3.2.2, the condition of the section of test rope on the head sheave can provide valuable information about the behaviour of the rope in service at large D/d ratios (in this case 85:1). An inspection was made of a section from EF (refer Figure 7). No wire breaks were found in any of the eight outer strands. Figure 10, below shows SEM images of the wear on the fibre rope after 218,287 cycles at 13.1% F_{min}. It can be seen that the fibre core has suffered some local minor abrasion, but on the whole is undamaged.

Rope	**D/d ratio (-)**	**Test load in rope (% F_{min})**	**Cycles at discard (in accordance with DIN 15,020*)**	**Cycles to failure (-)**
Standard Turboplast	20	13.1	180,000	528,822
Turboplast HM	20	13.1	123,300	436,574
Feyrer prediction**	20	13.1	89,200	205,800
Standard Turboplast	30	18.1	260,000	618,218
	30	18.1	200,000	626,954
Turboplast HM	30	18.1	508,000	932,680
	30	18.1	641,700	704,940
Feyrer prediction**	30	18.1	130,800	323,200

* That is whichever is first attained of either 9 wire breaks on 6d or 18 on 30d (DIN 15,020 [**12**]).

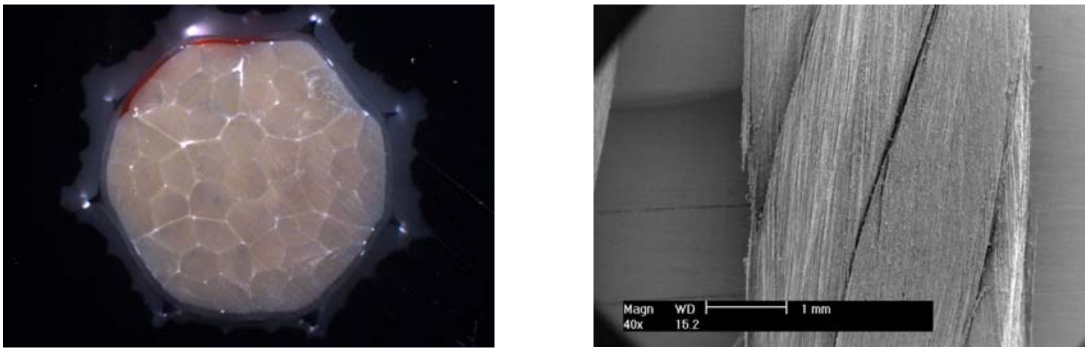
** Feyrer prediction made for a conventional eight strand rope with IWRC.

Table 6: Comparison of bending fatigue results for the Ø16 mm standard and composite ropes.



Typical outer strand condition, inside filaments are undamaged.

Filaments inside strand in good condition, only flattened corners damaged.



Core cross section: Strand deformation visible, only sharp corners cause limited local damage.

Typical core condition – some abrasion.

Figure 10: Typical condition of the Turboplast HM fibre core after operation on the drive sheave (D/d = 85) at load 13.1% F_{min} for 218,287 cycles.

5 Discussion and conclusions

The work presented here has shown that it is possible to design an aramid fibre core suitable for incorporation into a “standard” all steel plasticated rope. The combination of the braiding on the fibre core and the plastification have ensured that an integrated composite rope structure is obtained which exhibits good load sharing performance between fibre core and outer steel strands at both the operational and breaking loads. Breaking load results show that for the same diameter rope it is possible to attain loads in excess of F_{min} of the standard rope for composite ropes with both HM and SM aramid fibre cores.

Preliminary tensile and bending over sheave fatigue testing has proved very encouraging, although it is noted that more testing needs to be undertaken in order to gain further experience with the product. Other research is also being made investigating the use of different fibres (or the combination of fibres). Future work will also need to include an assessment of the rope’s torsional behaviour.

Having established the fundamental techniques to design a composite rope at a fairly small scale, the next stage in development will be to design, manufacture and test ropes of a suitable size for the mine hoisting application (typically Ø50 mm). Some experience is already available concerning the scaling of small fibre (test) ropes to the relatively larger ropes needed for service applications [**13**]. The previous work shows that some loss in performance in scaling up the size of a fibre rope can be expected, however, it is thought that adequate performance can still be achieved.

6 Acknowledgements

In a project of this size, there are inevitably many people who have contributed in many various ways. The authors are pleased to acknowledge and thank the following for their contributions: Dr Gerhard Rebel, CASAR Senior Consultant – mining ropes, who was involved in the initial stages of this project and has continued to be a valuable source of support and information. Acknowledgement is also due to the many staff at CASAR who assisted in the manufacture, termination and testing of the rope samples. Thanks are also due to the staff at Teijin Twaron BV, and in particular Mr Bertil van Berkel and Mr Ed Steijn who produced the SEM photos in Figure 10. Mr Sven Rosenberger (LIROS), Mr John Dodd (Millfield Enterprises) and Mr Graham du Plessis (DRA Tech Services Ltd.) also gave freely of their time and advice in various aspects of this work, their help is also much appreciated.

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