Austro2007/FORMEC´07: Meeting the Needs of Tomorrows´ Forests – New Developments in Forest
Engineering, October 7 – 11, 2007, Vienna and Heiligenkreuz – Austria

FURTHER DEVELOPMENTS OF SYNTHETIC ROPES FOR LOGGING APPLICATIONS IN FORESTRY

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Keywords: synthetic ropes, wear mechanisms, rope life, end connectors.

Abstract: *Based on long-time experience in the industrial use of both synthetic ropes and steel wire ropes, Teufelberger started research and development in synthetic ropes for logging applications in 2005. Practical tests were done in tight cooperation with the "Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW)".*

For some years the benefits of synthetic ropes in logging have been reported (see also Garland J.J., 2004a, Oregon State University): pronounced improvement of working conditions in manual harvesting, consequentially increased productivity due to the weight reduction of the rope by about 80 % as compared to steel as well as reduction of accidents.

This paper presents results of lab and practice tests for fibre ropes made of Dyneema© combined with other synthetic fibres. Newly developed technical solutions for the rough conditions of logging help maintain the excellent technical properties of Dyneema© for a longer time while improving abrasion resistance and providing an indication of rope wear / rope life. Work also focused on the design of end terminations/connectors with little compressional force. With Stratos logging ropes the use of synthetic ropes in logging has become practicable and leads to cost savings that make them pay off.

1. Introduction

The introduction of the second generation of synthetic polymer fibres, i.e. of high-modulus, high-tenacity fibres in the last quarter of the 20th century opened a new material source for fibre ropes. With the development of high-modulus polyethylene (HMPE, Dyneema©) fibres a material has become available that is stronger than steel on an area basis and about 10 times stronger on a weight basis (see table 1; data for polyester fibre (PET) as a well-known commodity fibre are included for comparison). It stands to reason that there is a high advantage of HMPE over steel wire rope in applications where weight is a critical factor – an advantage that may well justify a higher material price.

One application in which weight plays the major role is logging and especially mountain logging. The use of HMPE fibre ropes as a substitute for steel wire ropes

- leads to a significant reduction of work loads (ergonomic aspect),
- reduces the potential for accidents as it eliminates wire break that may lead to punctures and as it reduces fatigue which is often the cause of accidents,
- pays (economic aspect) as task times are significantly reduced, therefore shortening preparation time and increasing productive harvesting time.

Table 1: Tensile properties of steel wire, high-modulus polyethylene and polyester fibres
(McKenna, Hearle, O'Hear, 2004)

quantity	**unit**	**steel wire**	**HM-PE**	**PET**
density	[g/cm³]	7.85	0.97	1.38
strength per unit area	[MPa]~[N/mm²]	2600	3400	1130
strength per weight [1] (tenacity)	[cN/tex]	33	350	82

As regards the ergonomic aspect, extensive studies have been performed by the Forest Engineering Department of Oregon State University (Garland et al., 2002; Garland et al., 2004a). These studies compare the use of steel wire rope to synthetic fibre rope and show that upon use of HMPE ropes heart rates are reduced, recovery after exertion is improved and that workers subjectively assess work loads as reduced.

Depending on the logging application, task times are reduced. Dragging a synthetic rope uphill takes only approx. 25% of the time used for a wire rope. In skidding, again out hauling of the rope takes only 50% time with a synthetic rope whereas further tasks like hooking and unhooking or winching in are only shortened by a minor amount (Garland et al., 2004a). Similar magnitudes are given by a study performed by HAWK Fachhochschule Göttingen, Germany in 2004, where workers estimate that work power doubled during the use of Dyneema© rope in winch applications (Schultze et al., 2004).

Our field test showed that in the use of synthetic ropes as a guyline for a yarder, overall preparation time is reduced by 50%. Based on data provided by a major logging company in Austria, installation time for guylines may be assumed as one hour, meaning a reduction of 30 minutes or rather a respective increase of harvesting time. Assuming 72 installations per year this gain of harvesting time sums up to 36 hours per year or 300 cubic metres of solid timber more to be harvested. Additionally, installation may be done by two workers instead of four. We have developed a calculation tool to show the benefit of the synthetic rope. Contrasting the benefit with the higher cost of a synthetic rope indicates amortization within 6 to 12 months.

Change from a steel wire rope to a synthetic rope in winching is reported to pay off within a month of skidding. (Garland et al., 2003)

The critical points in the use of synthetic fibres in logging applications are high sensitivity of HMPE to lateral forces (compression) and difficulties in assessing remaining rope life. As steel wire rope end connectors often work due to compressional forces these devices cannot easily be used on synthetic fibre ropes. Besides, lateral forces are exerted to the winch line when it is wound on the drum. It has been our major concern to find means of assessing remaining rope life and to develop end connectors that are suitable both for the synthetic rope and the application in question.

Focus has been on guylines for yarders and for intermediate supports, synthetic extension lines for wire skylines, winch lines for skidders and chokers. Wear mechanisms for these applications were considered and lab tests as well as field tests carried out accordingly.

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[1] Correctly, the quantity considered is strength per weight per length as equal lengths of fibres are compared. For the sake of understanding, we have called this quantity "strength per weight" instead of "strength per weight per length" or "strength per linear density".

2. Applications and Wear Mechanisms

2.1 Static Applications

Static applications in this report include guylines for yarders and intermediate support trees (figures 1 and 2) as well as synthetic extensions for steel wire skylines. A schematic picture shows the use of these synthetic extensions (figures 3 and 4).

Figure 1: Synthetic guylines *Stratos Anchor* for yarder

Figure 2: Synthetic guyline *Stratos Support* for intermediate support tree

Figure 3: Synthetic extension line *Stratos Extension*

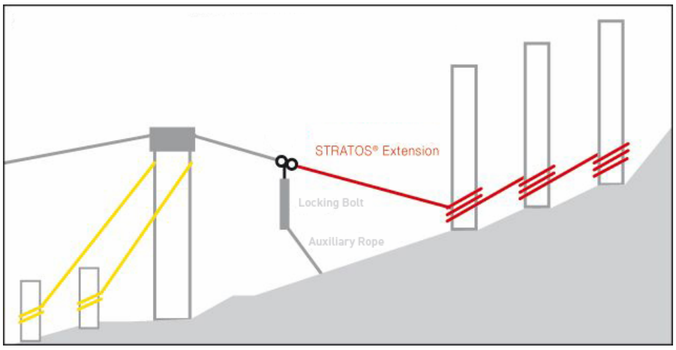

Figure 4: Scheme of the use of *Stratos Extension*

The properties required by the static applications described are visible in figures 1 to 3.:

- high abrasion resistance: The rope end is usually wrapped around a tree stump where it is exposed to the rough surface of the tree bark and at the same time “cuts” into the tree stump under high tensile load.
- good tension fatigue: The rope is not exposed to a constant load but may see load cycles, e.g. for a 22mm steel wire rope 3.5 to 5.5 kN were measured.
- good bending fatigue: At the top of the yarder the rope is subject to cycling over sheaves. Due to changes in load (see tension fatigue) minor rope movement on the sheaves must be considered.
- exclusion of torsion: Torsion in the rope leads to uneven distribution of load among the rope strands and therefore to a reduction in overall rope strength.

Besides, HMPE requires low lateral stress, which must be considered in the design of the end connector.

2.2 Winch Lines

In winch lines as shown in figure 5 abrasion resistance is an even more important issue than with static line applications. Winch lines are often dragged along the forest soil and therefore subject to severe abrading conditions. Bending and tension wear are also reported for winch lines (Schultze et al., 2004).

Figure 5: Synthetic winch line *Stratos Winch*

High lateral forces are exerted to the winch line when it is wound on the drum. After 7 months of use the part of *Stratos Winch* wound on the drum was heavily distorted and had a nearly triangular cross-sectional shape. The tensile strength of this part had, however, only decreased by a few percent.

It is a common procedure to re-do a wire rope end because of damage. As the same occurs to synthetic winch lines, a rope connector that can easily be repaired is a must. Schultze et al. even recommend to re-use the rest of the rope by re-connecting it with a long-splice and to turn the rope leading to more even wear (Schultze et al., 2004).

2.3 Chokers

Figure 6: Synthetic choker line *Stratos Choker*

Due to the shorter length of chokers the weight reduction stays in the background as compared to the other applications described and the absence of jaggers and reduced risk of injuries becomes of higher significance. The synthetic rope's flexibility makes it easy to work with.

As with winch lines, abrasion is the most critical wear mechanism: Choker lines are not only dragged along the forest soil but also rub against the tree bark. Figure 6 shows a synthetic choker using a standard steel wire choker nubbin and bell configuration.

2.4 Measurement of Fatigue Resistance

The most important wear mechanisms in the quoted logging applications may be summarized as bending fatigue, tension fatigue, torsion and abrasion. Abrasion resistance is dealt with separately (see chapter 3.) as external abrasion "is not considered fatigue" (McKenna, Hearle, O'Hear, 2004) and as extensive studies of the BFW focused on the topic of abrasion and abrasion resistance and deserve a separate chapter.

Bending fatigue (also: flex fatigue) means the effect of bending of the rope structure, e.g. when guylines run over sheaves like at the top of the yarder. The rope is subject to compressional forces on the inside radius of a bend and to tension on the outside radius. Flex fatigue depends on many variables like fibre material, sheave surface material, rope construction, load levels and frequency, the probably strongest influence being D/d ratio (D being the diameter of the sheave, d the diameter of the rope; large D/d ratios increase rope life) (McKenna, Hearle, O'Hear, 2004).

We tried to calculate how many bending-cycles one particular piece of rope may see and made the following assumptions: During one go of the carriage along the skyline, the guyline is assumed to be exposed to 10 load increases that lead to minor movements on the sheave. With six goes per hour and 10 hours per day, the same piece of rope would be subject to 600 bending cycles per day. With 15 days of harvesting in one place, that part of the rope would be exerted to 9,000 bending cycles. After the next installation the rope piece is most likely to be in a different place and not at the top sheave again.

Therefore the following test was performed: A *Stratos Anchor* 22 mm was subject to a bending fatigue test of 10,000 cycles with bending in one direction under a constant load of 80 kN. The diameter of the pulley (pulley groove: 20 mm) was 280 mm leading to a D/d ratio of 9.7 to 12 (as the rope is slightly oval). The rope was inspected after every 1,000 cycles and in all cases no wear was detectable visually apart from the rope running flat in the bending area. After 10,000 cycles the tensile strength of this "used" rope was measured and no strength loss was found.

Tension fatigue refers to rope wear due to cyclic loading and unloading, which primarily leads to internal fibre abrasion followed by filament breakage and therefore loss of strength. Tension fatigue is again dependent on fibre material as well as load difference (between minimum and maximum load), load level (mean load) and frequency. Internal abrasion being the key to tension fatigue, the performance of the fibres is strongly influenced by fibre finishes.

Data show that “the tension fatigue life of polyester ropes is greater than that of […] wire ropes. Indications are that a similar situation exists for […] HMPE ropes” (McKenna, Hearle, O’Hear, 2004). These findings give us confidence that HMPE ropes can replace steel wire ropes without having to expect problems as far as tension fatigue is concerned. More testing is on the way to support this confidence by data.

Tension fatigue must not be confused with overloading, which does not refer to a slow deterioration of rope strength but means excessive tension or shock loading. This type of damage is reported to be difficult to detect by visual or tactile inspection (McKenna, Hearle, O’Hear, 2004). *Stratos* Logging Ropes try to overcome this problem with the help of a special rope pattern: It is made of lines at regular and relatively short intervals. Differences in inter-line distance - as may occur as the result of overloading – are easily visible and a clear indication of some overload event (see figure 7).

Torsion is supposed to reduce rope strength as it leads to unbalanced loads on rope strands. Tests showing the influence of torsion on rope strength were carried out by Tension Technology International (funded by the Marine Accident Investigation Board). A 22mm *Stratos Anchor* was used and led to the results shown in table 2.

Table 2: Test results of influence of rotation on rope strength of a 22mm *Stratos Anchor*
(O’Hear, Nichols, 2006)

twist [turns/m]	residual strength [%]
1	96
3,5	85
5,5	56

The data show that a high twist that seems unlikely in use is necessary to substantially reduce rope strength. Nevertheless, *Stratos* Logging Ropes are equipped with a special rope pattern to make the user aware of rope twist immediately (see figure 7).

Figure 7: rope pattern of Stratos Logging Ropes : straight lines indicate torsion, cross lines indicate overloading

In conclusion, the data indicate that bending fatigue, tension fatigue and torsion are relevant wear mechanisms in logging, but tension fatigue is reportedly better of HMPE ropes than of steel wire ropes, the amount of bending on a guyline does not affect the rope and torsion is not likely to be so high as to lead to a deterioration of rope strength. Moreover, the *Stratos* Logging Rope pattern indicates torsion and overloading or other incidences that may lead to local rope elongation.

3. Abrasion Resistance

Ropes in logging are confronted with rough abrading conditions: forest soil, tree barks, branches etc. most likely under high loads. This holds true for steel wire and synthetic fibre ropes. While abrasion and wear of steel wire ropes can be assessed on the basis of a specified number of broken wires, synthetic ropes become fuzzy and eventually this fuzziness may become so prominent as to hide the initial braid structure.

It has proven difficult to assess remaining rope life and strength loss from the appearance of a fibre rope (Takumi, 1997). Pilkerton et al. gave some indication on rope life in 2003 and reported that “synthetic rope initially fuzzes up from broken filaments that produce a protective cushion but when braided rope is worn 25% from abrasion it should be replaced” (Pilkerton, Garland et al., 2003). Nevertheless, they still reported in 2004 that wear and replacement criteria were needed (Garland et al., 2004a).

With *Stratos* Logging Ropes a new way has been found to resolve this issue. The ropes are constructed as cover-core ropes with a synthetic abrasion resistant cover protecting the load bearing HMPE core. The cover does not contribute to the rope strength. Any damage of the cover by abrasion will therefore not reduce the strength of the core, which has been confirmed by tests (see below).

In order to simulate rope wear acceleratedly under conditions to be expected in logging a test unit was built with the support of the Federal Research and Training Centre for Forests in Gmunden. These dynamic wear tests (together with further lab tests) gave us a sound basis for developing an optimized rope cover and are the basis for rope life assessment and the definition of replacement criteria for synthetic ropes as compared to steel wire ropes.

For planning the test track the following criteria had to be kept in mind:

- The test track has to be suitable for both chokers and winch lines made of either synthetic fibre or steel wire simulating dragging,
- the test track has to be the closest possible approximation of most severe use in logging,
- the conditions for the ropes have to be virtually constant throughout the test series,
- the results of the test units have to be comparable,
- the conditions of a test series have to be reproducible,
- changes of the samples and change of direction have to be automated to the greatest possible extent and have to be simple.

Bearing these requirements in mind, a test track of about 40m length and 3m width was equipped with a rough surface closely simulating extreme conditions in logging so as to accordingly expect fast wear of the rope samples. About 20 cm of rough limestone gravel (grain size 0/32) mixed with about 25% humus were put on a coarse gravel bed. The track was compressed and rolled.

In order to simulate fixed obstacles in out hauling and to prevent the track from gradual depression seven concrete sleepers in cross direction were dug into the track at a distance of 3.5m. The sleepers protruded the track surface by about 3 cm. At one end of the test track a buffer stop was set down for testing maximum potential load. The load that had to be dragged was about 1500 kg in weight and consisted of two joined beech logs and additional concrete weights. This test load was dragged to and fro with the help of diverter pulleys and a double drum winch.

Straps were attached to each log end. Yokes were fixed between the chokers and the winch line to even out load differences and to ensure similar loads on each of the four chokers. This test design made it possible to make four tests on chokers and one test on a winch line in one go (see figures 8 and 9). Chokers are tested for abrasion resistance, the winch line may be judged by its winding properties.

On an average 50 cycles (1 go in one direction = 1 cycle) were carried out until wear of the chokers became visible. One test set consisted of 5 rope sample sets. Each test set was started and ended with steel wire ropes. On the one hand, these steel wire rope samples were tested for reference, on the other hand, the conditions of the test track were checked for possible changes during the test set. The second, third and fourth rope sample sets were different synthetic fibre ropes with one of these rope sample sets being the best in the preceding test set and the other two being new developments. This procedure ensures good test reproducibility.

The change of rope wear was evaluated and documented with the help of photos. Pictures were taken at regular intervals. The rope quality was assessed after measurement of remaining tensile strength of the worn rope samples in the lab. All ropes in table 3 are without coating. Tensile strength results refer to the rope including sewn ends (3 sewing patterns).

Figure 8: test track design

Figure 9: beech logs with concrete weights numbers refer to test positions 1 to 4

The following table and diagram show the results of one test set.

Table 3: Results of abrasion tests

				tensile strength [kN]					
	rope make	**diameter [mm]**	**linear density [g/m]**	**new rope**	**used rope position 1**	**used rope position 2**	**used rope position 3**	**used rope position 4**	**average of positions 1-4**
steel wire rope 1st run	216 WS+SC	11.0	479.0	83.1	79.9	73.6	61.7	74.5	72.4
steel wire rope 2nd run	216 WS+SC	11.0	479.0	83.1	80.0	65.8	68.0	81.7	73.9
polyester	HMPE core - PET cover	13.3	117.4	63.3	70.7	38.2	58.4	72.7	60.0
HMPE (Dyneema)	HMPE core - HMPE cover	13.0	94.7	63.5	78.6	77.8	77.6	78.0	78.0
LC-PES (Vectran)	HMPE core - Vectran cover	13.5	116.8	66.3	67.2	69.1	63.9	65.6	66.5
steel wire rope 3rd run	216 WS+SC	11.0	479.0	83.1	84.0	81.4	80.1	83.1	82.2

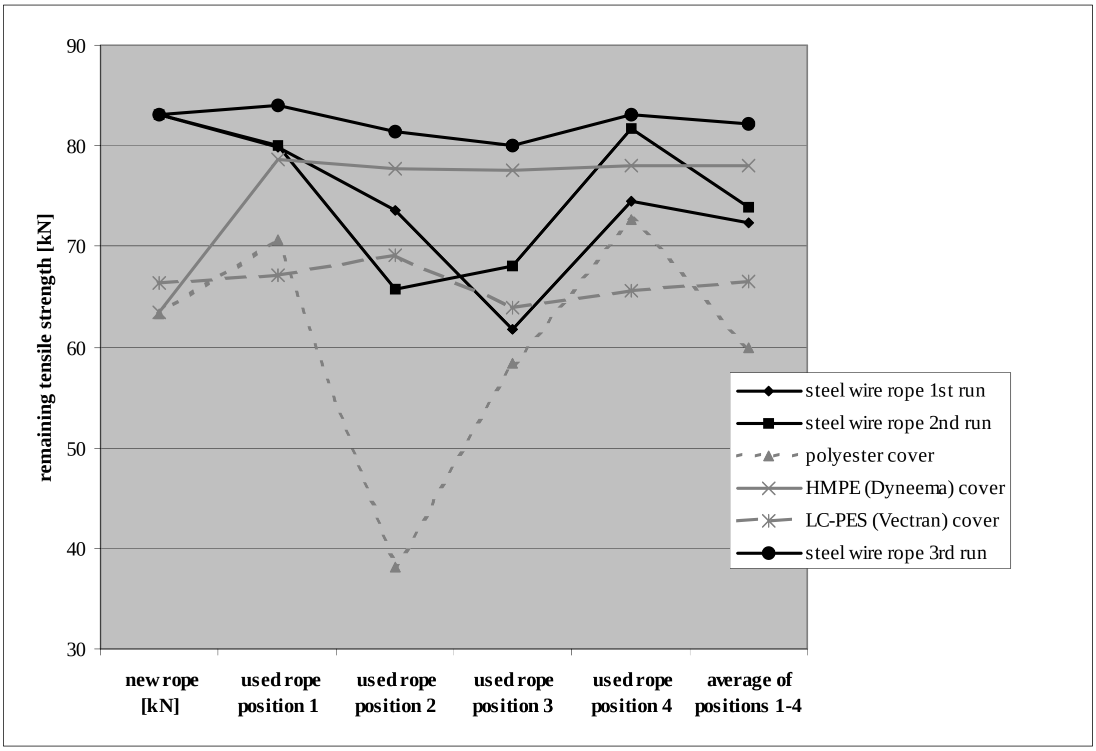

Figure 10: Diagram visualizing results of abrasion test

The results indicate that there are differences in position with positions 2 and 3 being consistently more abrading than positions 1 and 4. Steel wire rope wear is reproducible (1st and 2nd runs), but the test track loses some abrasiveness in the course of the test set (3rd run). The order of tests therefore must be taken into account when making cover assessment: Polyester must have seen higher abrasion than Vectran. HMPE shows promising properties and proves first choice not only for the core but also for the cover. Polyester can do under less abrasive conditions and is used in *Stratos Anchor*.

The steel wire chokers were clearly past their rope life after the test and showed only little more tensile strength than the synthetic fibre chokers. In all synthetic fibre chokers the cover was still intact with the exception of PET cover in positions 2 and 3. The cover of position 2 was severely damaged, the cover of position 3 was damaged to a minor extent. In those cases where the cover was damaged (this was also confirmed by further test sets) the core was exposed to abrasion and dirt and lost strength immediately and to a high extent. HMPE ropes showed higher tensile strength after use than before, which may be attributed to bedding-in and in-situ stretching of the rope.

These findings lead us to the conclusion that a damaged cover is a clear indication that the Dyneema© rope must be disposed of, whereas Dyneema© ropes with an intact cover that still protects the core have sufficient remaining tensile strength.

4. End Connectors

The use of wire rope end connectors on synthetic fibre rope is not immediately possible. Most wire rope end connectors work by means of external pressure (lateral force; clamping). High local lateral force, however, is most disadvantageous to HMPE and other high modulus synthetic fibres and reduces their tensile strength considerably. Most obviously, a rope – and also a synthetic fibre rope – "is only as strong as its weakest link, and this is often the termination" (McKenna, Hearle, O'Hear, 2004).

Depending on the use of the rope and its termination application specific criteria for the end connectors were found:

- end connectors for static applications must be able to bear high loads,
- connectors of synthetic extensions to wire ropes must be designed in a way to prevent potential rotation of the (laid) wire rope from propagating to the synthetic fibre rope,
- stoppers on a winch line must bear high loads, protect the rope termination against abrasion and be easy to repair,
- connectors of the winch line to the winch must deliberately break at a certain load for safety reasons,
- choker ends should be able to be used with standard steel wire choker configurations as these are more easily available than special solutions.

An enormous number of tests had to be carried out in order to find the best kind of rope terminations. In several rather complicated constructions using basically steel bolts as a stopper for a winch line, we found that the steel construction would be distorted and badly damaged while the synthetic fibre rope would still be fine.

End connectors that ought to bear high loads, i.e. end connectors for static applications, are best designed by splicing. Buried eye splices show smallest strength loss as compared to the rope's free length (Garland et al., 2004b). The eyes can be further connected with shackles and the like. Whenever one rope end is fixed to and wrapped around a tree trunk the rope and rope end must be protected against abrasive wear. The best result was gained with a leather cover around the core/cover-rope. Furthermore, abrasion resistance can be adjusted to the necessary level by choosing a suitable cover material (HMPE for most severe conditions like in rope extensions, PES is less rough circumstances like in guylines; see chapter 3.).

In guylines for support trees a special sling attached to the rope was developed to further secure the rope against slippage due to movements of the support trees. These slings are sewn unto the rope at regular intervals and are further protected by an abrasion resistant cloth (patent pending). This protecting cover can easily be removed from the sling needed for installation of the guyline (see figure 11).

Connections between synthetic ropes *Stratos Extension* and (laid) wire ropes must be fixed with a locking bolt to avoid propagating rotation as described above (see figure 12).

Two types of stopper on our winch rope *Stratos Winch* have proven to be practical: One of them is based on an eye splice and can therefore be repaired on the spot; the other one is a resin socketed termination the repair of which takes a workshop. In both cases, the fibres of the rope end are protected against compressional forces by a steel casing. Figure 15 shows Stratos Winch after 240 uses.

Figure 11: Rope slings (red) on guyline for support tree

Figure 12: *Stratos Extension* connection with locking bolt

Figure 13: Splice based end

Figure 14: socketed termination

Figure 15: Stratos Winch after 240 uses

As for *Stratos Choker*, sewn ends have stood the test. They can be produced with highly reproducible strengths. We have, admittedly, had the experience that the bends on standard end configuration for steel wire chokers are rather narrow and induce rope break at the bend. Choker lifetime seems sufficient for a start but ought to be further improved. More work needs to be done to design special end connectors for synthetic choker. Some users might, however, prefer to use standard wire rope hardware, which is possible even now.

5. Conclusion

In the course of two years, Teufelberger have developed new synthetic fibre ropes of cover/core-construction for various logging applications: guylines for yarders (*Stratos Anchor*) as well as for support trees (*Stratos Support*), synthetic rope extensions for wire rope skylines (*Stratos Extension*), winch lines (*Stratos Winch*) and chokers (*Stratos Choker*). The ropes had to stand trials in the lab (to test the influence and relevance of wear mechanisms), on a test track simulating application (most of all to test abrasion resistance) and in the field. The cover/core construction makes it possible to use a special rope pattern as an indicator for torsion and overloading. An intact cover protects the core and indicates good tensile strength characteristics. End connections and terminations based on splicing and sewing have stood the test especially in static applications. More work needs to be done to optimize choker ends, though.

These findings make the use of synthetic fibre ropes in logging practicable. 80% weight reduction leading to positive ergonomic effects and a reduced number of accidents are good reasons for synthetic logging ropes, higher productivity most probably being the best.

6. Acknowledgements

Our thanks go to Erich Ruehrnoessl, who has been in charge of the project on the use of synthetic ropes in logging and who has done a remarkable job. We would like to thank Armin Ribis for preparing the economic details and Alexander Strubreiter for doing the marketing and providing us with his documentation.

Nick O'Hear of Tension Technology International (TTI) has been a great partner in discussions and allowed us to use his data on rope rotation, gratefully funded by the Marine Accident Investigation Board.

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