Use of High Strength Fibre Ropes in Multi-Rope Kinematic Robot Systems

Jens C. Weis, Björn Ernst and Karl-Heinz Wehking

Abstract High strength fibre ropes are facing a strongly increasing interest for rope driven applications. Basic characteristics such as strength are already competitive or even outperforming wire ropes; however other limitations still prevent their full reliable industrial use. One particular application where the advantages of high strength fibre ropes do have an extraordinary important effect on the usability of the application is the use in robot systems with multi-rope kinematics. Basic requirements of these systems are (among others) high accuracy paired with a high efficiency, which means high process velocities as well as high accelerations and decelerations. Many tests have already been conducted to simulate a wide range of load settings—however up to date testing of fibre ropes in high speed usage is still mostly missing. This article describes the state of the art of high strength fibre rope usage in material handling, discusses advantages and disadvantages of these ropes and points out the most important challenges for research and improvement of rope driven robot systems.

1 Introduction

At present high strength fibre ropes are already used as high efficient suspension elements and are therefore a good choice for a wide range of applications, such as manufacturing processes or materials handling processes. Conventional materials handling systems driven by wire ropes are coming to their limits with regards to high process speeds and minimisation of process times, so there is a significant trend towards establishment of high strength fibre ropes in these applications where low weight, high strength and low inertia are basic prerequisites. Analyses focusing

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on behaviour of high strength fibre ropes at high dynamic usage are not available up to today, so obviously there is demand to research on their dynamic resistance. Fast loading, changing loads, load oscillations and the influences on related rope characteristics (e.g. bending fatigue) also need to be analysed and for later use in practice.

One example from the field of materials handling processes are robot systems which are born by multi-rope kinematics. For an effective and economic use of these systems high accelerations and velocities (i.e. low process times) are mandatory. As these robot systems also need a high positioning precision it is obvious that focusing on these applications allows development of basic fundamentals regarding the design of configurable large-scale rope kinematics for rope-born robots as well as for further rope applications.

2 High Strength Fibre Rope Research

2.1 State of Research

Standards for design and testing of high strength fibre ropes in service are available at present and even partially defined in different national and international standards [1–4]. However, to date almost all of these are dealing with basics only and most of them have been developed for maritime use and are limited to this scope only. These standards usually address testing of the ultimate break load UBL, possible weight and modulus test methods as well as handling suggestions, but they do not cover lifetime estimations or prediction methods. Additional influences which might result from high-dynamic usage (e.g. additional friction, heat buildup and wear) are so far not considered and are therefore usually taken into account by using high safety factors which are based on experience.

Since there are so many different fields of applications for high strength fibre ropes, it seems generally not possible to define one material or construction which would suit every application so a variety of rope materials and rope constructions is usually suitable to meet the specific needs of a particular application [5]. Regarding the application of robot systems with multi-rope kinematics this situation results in excessive experimental work in order to obtain reliable data about the long-term behaviour of the ropes used under combined loading and with respect to highly dynamic influences as well as to define reliable and safe discard criteria. Figure 1 gives a schematic overview on the current state of high strength fibre rope research with respect to different deterioration mechanisms and system parameters of high strength fibre ropes [6]. As can be seen (among others) is that the influence of velocity and acceleration on rope life is almost fully unknown.

It can be summarized that—despite multiple research and industrial based efforts—to date there is a lack of knowledge in the field of fibre rope technology. Many challenges and questions still remain to be solved and answered.

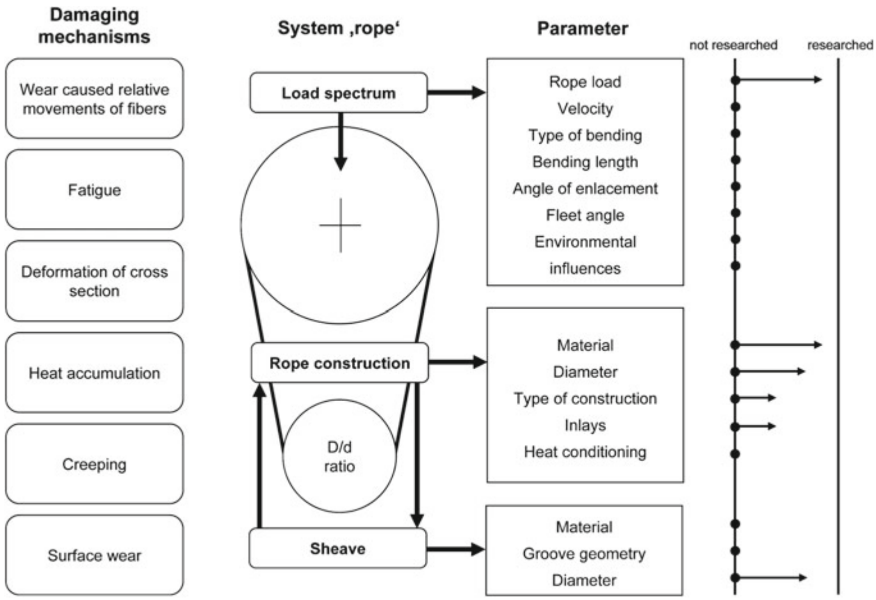

Fig. 1 Damaging mechanisms and system parameters at running fibre ropes (analog [6])

2.2 High Strength Fibre Ropes

High strength fibre ropes comprise different characteristics depending on their basic material(s), their construction and their manufacturing processes.

Typical characteristics of high strength fibre ropes include small diameter, low specific weight, low stretch, torque balance (depending on construction) with good bend-over-sheave fatigue life as well as outstanding tension-tension fatigue life. Table 1 additionally gives a general understanding of the material properties of different synthetic fibres [7]. Regarding the physical properties and the material characteristics shown in Table 1 especially high strength fibre ropes might seem to be of excellent suitability for the intended use in robot systems with multi-rope kinematics. Compared to wire ropes one of the main advantages of high strength fibre ropes may be seen in the fact that these show no need of (re-)lubrication and may therefore be used in many applications where this requirement is essential. The main disadvantages of high strength fibre ropes (compared to wire ropes) may at the time be seen in a low sensitivity against high temperatures, low lateral stiffness and a lack of standardised discard criteria.

Table 1 Matrix of comparison of material properties of different synthetic fibres [7]

Material grade of high-strength synthetic fibres	[E]	PA Polyamide PA 6.6 PA 6	PES Polyester	PP Polypropylene	HMPE High-molecular polyethylene	Aromatic-Polyamide (Aramide)	PBO (Zylon)	LCP Aromatic polyester (Vectran)
Trade name		Perlon, Nylon, Nylsuisse Enkalon	Diolen, Trevira, Dacron, Tersuisse	Hostaien Softlene, Leolene	Dyneema, Sektra	Twaron, Kevlar, Technora	Zylon	Vectran
Fibre count breaking load or breaking length in km	cN/tex	65–85	60–85	more than 47	280–400	200–250	370	220–250
Tensile strength	N/mm^2	741–969	741–969	300–500	2,688–3,648	2,880–3,600	5,624	3,102–3,525
Breaking elongation	%	12–25	10–20	15–25	3.8	2–4	2.5	3.3
Density	kg/dm^3	1.14	1.38	0.91	0.95–0.96	1.44	1.52	1.41
Moisture expansion	%	5–10	=0	=0	=0	=0	5	=0
Absorbtion of water/humidity	%	1–7	0.5–2	0	0	2–5	0.6	1
Melting point	°C	215 250	260	165	150	480	650	330
Light resonance		Good	Very good	Only good if equipped	Good	Moderate up to poor	Poor	Poor
Chemical resistance		Acidic unresistant, stable to weak bases	Acidic resistant but alkail unresistant	Acidic and alkali-resistant	Resistant apart from strength oxidant	Acidic and alkali-resistant	Acidic and alkali-resistant	Acidic and alkali-resistant (apart from dissolver)
Other negative properties		Hardening due to atmospheric influence	Unresistant to shear strength	Low abrasion resistance	Low creep rupture strength, creeping approx. 15 % of MBL	Low shear strength and weak resistance up to low temperatures	Loses relevant tensile strength due to weathering and absorbtion of humidity	

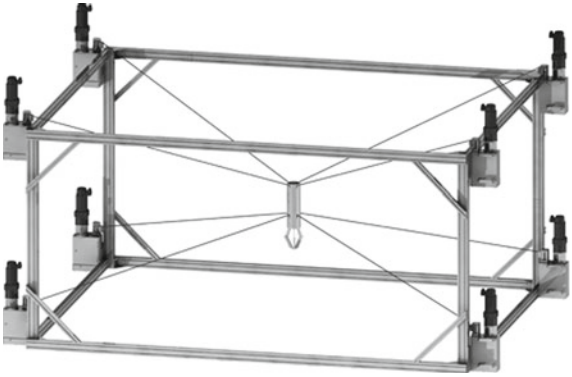

Fig. 2 Prototype of the rope-driven robot [8]

Fig. 3 HMPE fibre rope as used in the rope-driven robot (*scaled*)

2.3 Robot Systems with Multi-Rope Kinematics

Figure 2 shows the prototype of a multi-rope robot system built up at 'Fraunhofer Institute of Manufacturing, Engineering and Automation IPA' [8]. In this system the 'rope drive' comprises of eight similar winches which control eight suspension high strength fibre ropes which are connected to a picker. Coming from the winch, each rope passes two deflection sheaves and is then connected to the picker via a special end termination. When passing over the winch and the sheaves each of these ropes is paid out, bent, deflected and twisted in different angles and directions; thus, due to alternating payloads carried by the picker as well as these different angles and directions each rope obviously faces different loadings.

In the prototype shown at Fig. 2 high strength fibre ropes which consist of ultrahigh molecular weight polyethylene (UHMWPE) and a twelve braid strand construction with a nominal diameter of 2.5 mm and a minimum break load (MBL) of 5.8 kN were selected, see Fig. 3.

In this development stage the primary goal was the initial determination of the functionality of the system; testings did not include fatigue life testing (i.e. bending fatigue) of the used high strength fibre ropes.

3 High Strength Fibre Rope Testing

3.1 General

In the following chapters several possibilities and exemplary results of high strength fibre rope tests coming from so called 'running applications' conducted at the Institute of Mechanical Handling and Logistics (IFT) are described and summarized. The questions raised with regards to dynamic behavior and fatigue life characteristics of the high strength fibre ropes as they will occur in service of the described robot system (bending fatigue life, deterioration of UBL, tension- tension fatigue life, accelerations and velocities) have not been answered and quantified before. As described above these parameters are significant with regards to positioning accuracy of the picker and minimization of picking time as well as safety and economical service of the system (i.e. availability), which directly depends upon the proper functionality of all of the used high strength fibre ropes [9]. Thus, multiple tests are to be conducted before a high strength fibre rope may be approved for use in a particular application, especially if high safety against partial or complete failure of the system is required. Therefore, attention should be paid to the following [10]:

- specific strength and specific weight,
- bending fatigue life (cyclic bend over sheave performance CBOS),
- abrasion resistance,
- cutting performance,
- actuator performance (i.e. spooling behaviour, traction characteristics, etc),
- temperature and environmental boundary conditions,
- rope end terminations,
- discard criteria ,
- inspection intervals and inspection procedures.

3.2 Standard Cyclic Bend Over Sheave Testing (CBOS)

Analyses of the static strength behaviour of high strength fibre ropes are to date state of research (see Sect. 2.3). If high strength fibre ropes are not only tensile loaded, but bent over sheaves additionally or are stored on winches they are usually bent from straight state to bent state and back to straight state cyclically. When undergoing this bending process the single fibres and strands of the rope face alternating loadings regarding tension stress, bending stress and lateral pressure.

The determination and prediction of the lifetime of running high strength fibre ropes is limited to specific use in the industrial fields of lifting applications, offshore technology and mining [11]. Contributions determining the influences of the multiple, superposed stresses in the strands and fibres have been conducted by several authors but predominantly in the field of maritime applications, see e.g. Hobbs [12] and van Leeuwen [13]. Next to the stresses a use of high strength fibre ropes in 'running' applications is only possible because the strands and fibres move relatively against each other. Obviously, these relative movements between fibres and strands are constrained by friction and therefore lead to different types of surface wear.

Due to this surface wear of strands and fibres even an explicit appraisal of single fibre stresses would not provide reliable information regarding the lifetime of the strand (and the rope) to be expected in a specific application, even with defined load scenarios.

Fig. 4 CBOS testing machine for small rope diameters at the Institute of Mechanical Handling and Logistics, Stuttgart (IFT)

So today, the lifetime of high strength fibre ropes can be only determined with good precision in cyclic bend over sheave testing (CBOS). Figure 4 shows a typical CBOS test rig for the determination of the rope lifetime (i.e. bending cycles) under defined loading and bending conditions. This bending fatigue machine consists of a driven steel made deflection sheave and a changeable test sheave. It performs an oscillating movement with a predetermined stroke so the test rope changes from straight to bent and back to a straight state. The rope is therefore loaded by homogeneous bending cycles. The rope force is induced by a constant weight which is directly connected to the test sheave.

Systematic testing of running high strength fibre ropes at IFT started in 1997. In these CBOS tests the bending fatigue life characteristics and other behaviour relevant for the use of these ropes in practical service were investigated [14–17]. The results of the CBOS testings performed with a high strength fibre rope are displayed in Fig. 5 in a double logarithmic diagram [17]. The abscissa (x-axis) gives the specific (i.e. diameter-related) rope force, the ordinate (y-axis) the number of bending cycles until breakage. As can be seen, the bending fatigue life of the rope is reduced significantly if the rope force is increased at a constant D/d ratio. Figure 5 also gives the number of bending cycles to breakage of wire ropes which are known for their good bending fatigue life. It can be seen that at a comparably small D/d ratio of ten the bending fatigue life of the tested high strength fibre rope outperforms both wire rope constructions remarkably; this shows the general pertinence of high strength fibre ropes for use in running applications under certain conditions.

As can be seen from the diagram, if the specific rope force exceeds approximately 300 N/mm^2 the bending fatigue life until breakage of the rope is decreased disproportionally high. In the field of wire ropes this area, where the fatigue caused breakage of the rope turns into a forced rupture, is usually called 'Donandt- point' [18].

The CBOS test results gained at constant (low) speeds are fundamental data for later comparisons regarding additional influences such as high dynamics and parametric dimensioning of rope drives and rope drive components such as sheaves and winches. With a sufficient data basis of CBOS tests lifetime diagrams for several kinds of high strength fibre rope may be generated (compare Fig. 5).

3.3 Analysis Methods

The number of bending cycles to breakage and to the point of discard both depend on multiple parameters (i.e. rope load, D/d ratio, groove design, coating etc.). An appropriate method to analyse experimental bending fatigue test results and to gain a usable approach for the lifetime prediction is by use of multiple regression analyses. This method has proven to be very effective yet accurate and is widely established in the field of wire ropes.

For the high strength fibre ropes used in the robot system described above no dimensioning references (based on statistically determined large-scale studies as available in the field of wire ropes) are available. Based on single CBOS test series a lifetime formula based on multiple regression analysis for the determination of the number of bending cycles until breakage of the rope for small and medium diameter-related loads was generated, see Eq. 1 [14, 16]

$$\lg\overline{N} = b_0 + b_1 \lg\frac{Sd_0^2}{d^2 S_0} + b_2 \lg\frac{D}{d} + b_3 \frac{Sd_0^2}{d^2 S_0} \lg\frac{D}{d} \quad (1)$$

The estimated average number of bending cycles until breakage N is be calculated as function of the applied load S and the D/d ratio of rope and sheave. The unified load S_0 and the unified diameter d_0 are used to keep the equation non-dimensional in the sense of bending cycles until breakage of the rope. The regression coefficients b_i derive from the regression analysis of the experimental CBOS test results.

The results of the multiple regression analyses should be compared to the experimental results and analysed subsequently with statistical means. In wire rope research, the subsequent analysis of the performed regression calculations by means of coefficient of determination and standard deviation has proven to be effective [18].

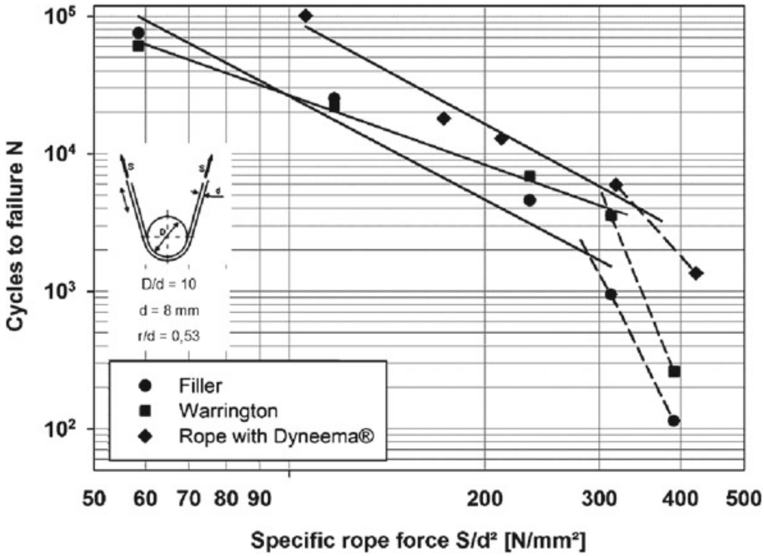

Fig. 5 Bending fatigue life of high strength fibre ropes and wire ropes [13]

The coefficient of determination describes the quality of the regression approach which was used for the analysis of the experimental test results, the standard deviation is used to analyse the degree of scatter of the experimental test results with regards to the chosen regression approach. In wire rope research, the logarithmic Gaussian distribution has proven to describe the failure probability of wire ropes with high accuracy [18].

3.4 Influence of High Accelerations and Velocity on Bending Fatigue Life

High accelerations and velocities of ropes in running applications are at present known only for steel wire ropes used in catapult systems (e.g. in fair rides such as [19] or on military aircraft carriers) but have not been quantified before. Sloan [20] exemplarily monitored the influence of the test speed during CBOS testing on the bending fatigue life of high strength fibre ropes. It can clearly be seen that an increase in cycling speed results in a significant decrease of the bending fatigue life of the tested high strength fibre rope, see Fig. 6.

With regards to the multi-rope robot system discussed above, an increase in velocity (i.e. decrease of process time) will also increase friction and wear. Taking into account the inertia of the picker, high tensile stresses and bending stresses in the ropes and significant rope elongations will make sophisticated controlling necessary

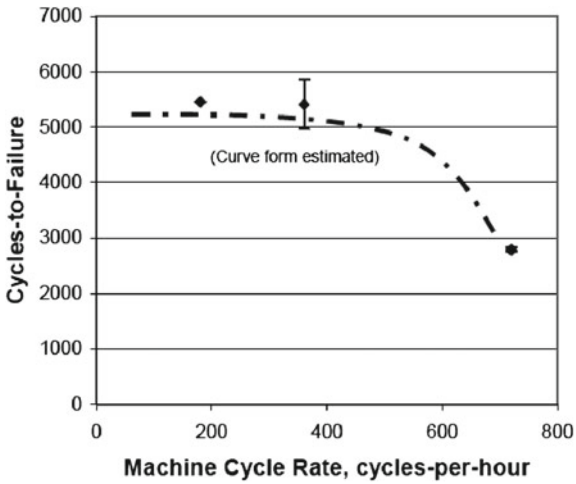

Fig. 6 Influence of test speed on the lifetime of a fibre rope [20]

in order to realize the required positioning accuracy of the picker. It is obvious that accelerations and velocities exert significant influence on the fatigue life of the used fibre ropes; this should be taken into account as early as possible, ideally already in the planning stage of the system with regards to reliability, availability and economic usage. Further research which focuses specifically on the suspension elements with regards to dynamic influences is recommended.

3.5 Major Trends

In the last years remarkable improvements in the bending performance of high strength fibre ropes in running applications where gained. Compared to steel wire ropes the bending performance at small D/d ratios is even better than for steel wire ropes [10]. IFT continuously tests bending fatigue life of high strength rope constructions in systematic CBOS testing series. Figure 7 exemplarily describes the trends of improvement of bending fatigue life of HMPE- fibre ropes (d = 8 mm) from 2007 to 2012. A remarkable increase of the bending fatigue life (i.e. bending cycles until breakage)—even for small D/d—ratios can be found.

Currently there are many efforts to optimize fibre rope constructions for use in running applications (e.g. [21, 22]). For example, a research project at the University of Chemnitz (Germany) called 'InnoZug' is at the time generating experimental, scientific knowledge on lifetime and wear mechanisms of non-coated high strength fibre ropes of several materials and constructions [23]; another research project at the University of Aachen (Germany) called 'Smart Rope' aims to develop a rope monitoring system which is capable of communicating the state of degradation of the rope in service [24]. The storage of fibre ropes on drums in single layer spooling is currently state of research [25], but as was found at the University of Clausthal

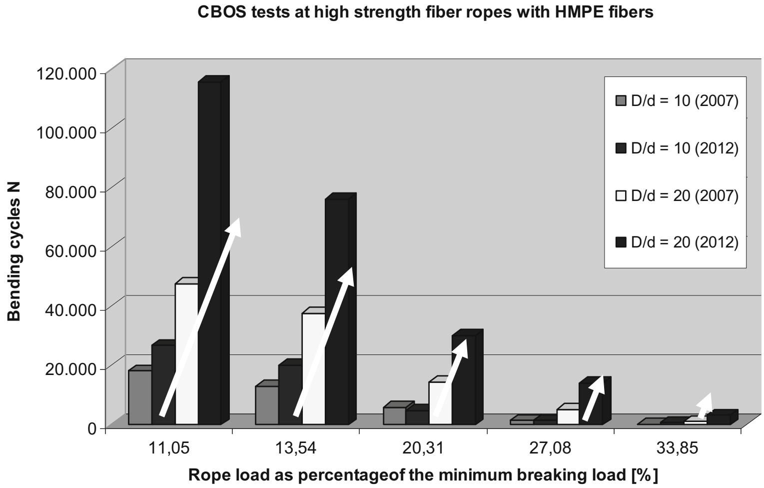

Fig. 7 Improvement of CBOS fatigue life from 2007 to 2012

(Germany) that there are specific requirements of the storage unit (i.e. winch) to be taken into account while used with fibre or fibre-cored rope constructions because of their low lateral stiffness [26]. A research project performed at IFT which investigates the usability of high strength fibre ropes for lifting in automated rack feeders is currently in its final phase. Within this research the focus is laid on the lifetime of the high strength fibre ropes with special interest on the elements of the rope drive (sheaves, winch, end terminations) with the goal to replace wire ropes the benefit of smaller engines, drive trains and outer dimensions of the systems.

Bending fatigue testing (especially CBOS testing) has shown to be the fundamental basis for validation of the choice of the right high strength fibre rope. Depending on the intended application, other influences need to be addressed and validated additionally (tension-tension testing, etc).

4 New Test Rig for Bending Fatigue Testing at High Accelerations

As described above high process accelerations/decelerations and velocities of the picker in the robot system result in bending and tension-tension loading of the used high strength fibre ropes.

In the first stage the primary focus was laid on the bending fatigue life of the high strength fibre ropes used in the system. As discussed, tension-tension fatigue life of the ropes needs to be addressed as well. Furthermore, high frictional loadings occur at the sheaves and winches between ropes and grooves. These cause premature

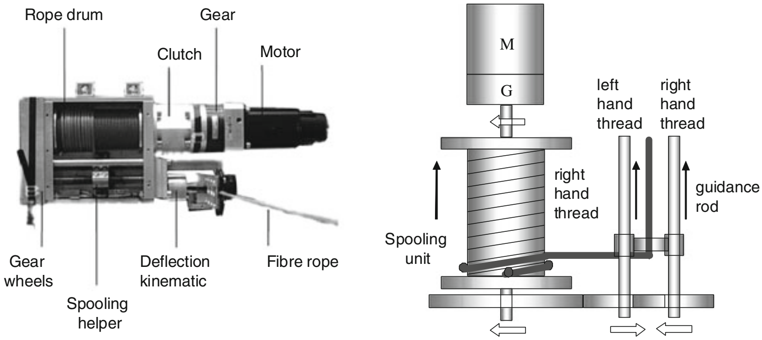

Fig. 8 Elements of the fibre rope winches (analog [8])

deterioration of the surfaces of the ropes which result in reductions of the ultimate break loads and premature levels of discard.

Figure 8 shows one of the winches as they are used in the robot system [8]. Each of the eight winches of the robot system consists of rope drum, drive chain, spooling helper and a special rope deflection sheave. The rope is spooled in single layer and guided via a customized deflection kinematic.

To evaluate the overall behaviour of the high strength fibre rope in the system the mere simulation of the spooling behaviour is not sufficient. For a precise determination of these (and other) mechanisms a new test rig was found to be necessary which is developed at IFT, see Fig. 9. In this test rig four winches for storage of the rope are attached at the upper end. The high strength fibre ropes run from the winches over a deflection sheave and back to the top where they are fixed via special end terminations, resulting in a double reeving. A test weight which is guided by slide bearings provides a constant, defined rope load during testing. As can be seen from the drawing, four high strength fibre ropes may be tested simultaneously for sufficient analyses of combined parameters.

Further details are included in order to make the test rig as versatile as possible regarding variation of test conditions and test parameters. Due to its design and dimensioning accelerations up to 10 m/s^2 may be realized which is approximately five times higher than accelerations in conventional lifting applications. For realization of these accelerations a minimum overall height of ten meters was found to be necessary. The test rig characteristics are summarized as following:

- variable load carrier for simulation of high tensile loads
- variable stroke / lifting height
- high modularity of the test rig components
- parallel testing of multiple ropes
- automatic visual monitoring of the rope condition

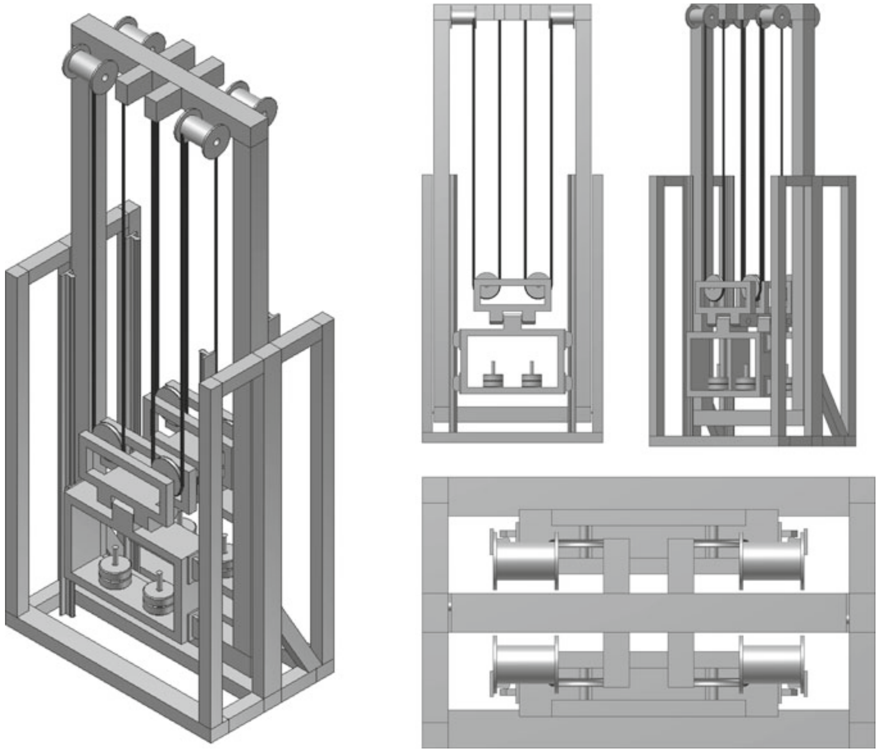

Fig. 9 Test rig for testing of accelerated high strength fibre ropes (schematic)

5 Summary

At present numerous endeavors are noticeable to establish lightweight high strength fibre ropes in running rope applications which comprise highly dynamic characteristics, such as in manufacturing processes and materials handling processes. Of course multiple other material handling applications can be found, but the robot system with multi-rope kinematics as described above seems one of the most potential applications for use of high strength fibre ropes. On the first prototype of this system multiple functional tests were conducted. However, additional expertise and experimental data of the fatigue life of the used high strength fibre ropes used in this application need to be gathered. This data and expertise is determined by means of fundamental experimental research—bending fatigue testing and tension-tension fatigue testing have proven to be adequate means to gain experience with regards to long term characteristics such as bending fatigue life, tension-tension fatigue life and resistance to high-dynamic influences of running high strength fibre ropes.

Wear has to be seen as crucial factor regarding the bending fatigue life of the high strength fibre ropes. Precise analysis methods of the actual fibre rope condition in service are mandatory for safe and reliable definition of service intervals and to guarantee a sufficient positioning accuracy required by the system over its lifetime.

In order to determine their long-term performance under high accelerations a new test rig is built. With this test rig basic fundamental approaches are analysed and quantified. Based on the experimental results gained thorough analyses are conducted to determine further parameters such as friction behaviour, wear, temperature as well as influence of contaminants etc. under laboratory conditions.

Furthermore, application-specific deterioration parameters are to be identified and reliable indicators for a safe level of discard are to be defined. Thus, sufficient recommendations for dimensioning and scaling regarding economic and ecological aspects may be defined and a sufficient lifetime and availability in service of the system may be achieved. The rope drive elements such as sheaves and winches for storage of rope, deflection systems and end terminations are optimised.

The long term goal of the basic and fundamental research work described is to establish high strength fibre ropes also in other rope drive applications as a substitute of steel wire ropes or to make the realization of new rope drives and systems possible.

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