Chair of Petroleum and Geothermal Energy Recovery

Master Thesis

Analysis and Simulation of a High-Performance Wire and Fibre Rope as Continuous Sucker Rod String

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Kurzfassung

Pferdekopfpumpen sind der meistgenutzte Typus unter den Artificial Lift-Systemen, welche in Öl- und Gasbohrungen verwendet werden, um die Produktion zu erhöhen. Der Sucker Rod-Strang, die Komponente die die oszillierende Bewegung des Surface Polished Rod zur Untergrundplunger überträgt, kann viele operative Komplikationen mit sich bringen. Von beschädigten und losgeschraubten Kopplungen zu zeitaufwendigen Prozeduren der Stangenbefestigung/Stangenabtrennung. Deshalb können durchgehende Stränge wie Drahtseile und synthetische Seile ein passender Ersatz für Stangenarrays sein.

In dieser Arbeit werden sowie die Leistung von Drahtseilen, hergestellt von der Voestalpine AG, als auch das Faserseil Dyneema®, hergestellt von DSM, von einer Computersoftware analysiert und simuliert. Die Ergebnisse beweisen, dass die Effizienz beider Konstruktionen sehr stark von der Geometrie der Bohrung, dem Pumpentyp und der Oberflächenkonstruktion abhängt. Sie zeigen außerdem, dass das Pumpen mit Draht- oder Faserseilen genauso produktiv wie mit herkömmlichen Gestängen sein kann, wenn man bestimmte Kennwerte wie Zugfestigkeit des Materials und Pumpenanschläge pro Minute berücksichtigt.

Schlagwörter: Sucker-rod pumpen ; Artificial Lift systemen ; Polished Rod ; Untergrundplunger ; Drahtseile ; synthetische Seile ; Zugfestigkeit ; Pumpenanschläge

Abstract

Sucker rod pumping is the most common type of artificial lift systems deployed in oil and gas wells to improve production. The sucker rod string, which is the component that transfers the reciprocating movement of the surface polished rod to the downhole pump plunger, is the source of several operational complications. From damaged rods and unscrewed couplings to time-consuming rod attachment/detachment procedures, the influence of these failures on the operational costs is substantial. Hence, continuous strings like wire ropes and synthetic ropes can be a convenient replacement for conventional rod strings.

In this work, the performance of a wire rope, designed by Voestalpine AG as well as a Dyneema® fiber rope designed by DSM are analyzed and simulated with a computer software package. The results prove that the efficiency of both designs highly depend on the geometry of the well, type of the pump and the surface structure. They also show that pumping with wire or fiber ropes can be just as productive, or surpasses the efficiency of a conventional sucker rod string as long as certain measures, such as material tensile strength and pumping SPM, are taken into advisement.

Keywords: sucker rod pumping ; artificial lift systems ; polished rod ; pump plunger ; wire rope ; synthetic rope ; tensile strength ; SPM ; continuous rod string

Abbreviations

API	American Petroleum Institute
ASTM	American Society of the International Association for Testing and Materials
BPD	Barrel per Day
C	Degrees Centigrade
cp.	Centi-Poise
CSR	Conventional Sucker Rod
CT	Coiled Tubing
ESP	Electric Submersible Pumps
FSR	Flexible Sucker Rod
ft.	Foot
HM-HT	High Modulus – High Tenacity
HMPE	High-Modulus Polyethylene
HPPE	Gel-spun HMPE
HRC	Rockwell C Hardness
HS	High-Strength
in.	Inch
IWRC	Independent Wire Rope Core
kPa	Kilo-Pascal
ksi	Kilo Pounds per Square Inch
lb	Pound
m.	Meter
MTBF	Mean Time between Failure
No.	Number
OD	Outer Diameter
OPEX	Operating Expense
PA	Polyamide
PCP	Progressive Cavity Pump
PES	Polyester
PPTA	Para-Phenylene Terephthalamide
psi	Pounds per Square Inch
SF	Safety Factor
SPM	Strokes per Minute
Sq. in.	Square Inch
SR	Sucker Rod
SRABS	Sucker Rod Anti-Buckling System
SRP	Sucker Rod Pump
TVD	True Vertical Depth
UHMWPE	Ultra-High Molecular Weight Polyethylene

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1 Introduction

Oil and gas production dates back to over a century ago. Ever since, science and innovation has taken an uphill road to improve the adopted techniques day by day. In the field of recovery and production alone, many developments have taken place especially in the area of artificial lift systems. Different pumping units have been introduced and modifications have been made on surface and downhole components to optimize their behaviour. Still, constant failures and costly repair jobs occur in the common pumping operations such as sucker rod units. Although rod pumping is one of the simplest and most flexible means of artificial lift, it is nevertheless prone to malfunction, specifically within the rod string.

Hence, novel approaches and ideas have surfaced to provide a means for modelling the behaviour of such a system and predict its weak points. Several computer programs assist engineers with the analysis of data while new inventions in surface and downhole facilities are being field tested.

The purpose of this work is to implement a prototype software and a newly designed pump in analysing the performance of a sucker rod pumping system that uses a continuous string instead of the commercially available sucker rods. The idea behind this proposed system is to eliminate the rod couplings, reduce the rod string loads and simplify the installation and transportation. These improvements will directly result in an increase the Mean Time between Failure (MTBF), minimization of energy consumption due and applicability of these setups in remote areas respectively.

This work starts with a brief explanation of fundamentals in Chapter 2. Later in Chapter 3, a thorough literature review was carried out to identify available or patented continuous sucker rod strings. After studying different methodologies, the application of wire ropes was brought to attention as a viable and practical option. Further investigation of wire ropes in Chapter 4 also brought up an idea to implement fibre ropes in sucker rod pumping systems and therefore their properties and potential was discussed in Chapter 5. In order to take advantage of the current technologies, a pre-stressed wire rope commonly used for suspension purposes and manufactured at Voestalpine AG in Austria along with a Dyneema® DM20 fibre rope mostly used in mooring purposes and developed by DSM company in the Netherlands were studied and later simulated with the prototype software. Certain setups were designed and multiple cases were considered, all of which can be found in Chapter 6. Lastly, the simulation results were discussed in Chapter 7. After a conclusion in Chapter 8, further improvements and recommendations are available in Chapter 9.

2 Fundamentals

This chapter explains the basic principles of artificial lift systems and describes the strengths and weaknesses of a sucker rod pumping unit concisely. An overview of the contributing parameters in design of such units will also be presented.

2.1 Artificial Lift Systems in a glance

Artificial Lift methods are generally used to compensate for the losses in production of a well. When the natural drive energy of a reservoir is not sufficient or is diminishing, these processes are employed to sustain and recover the production rate. Most wells will eventually require such assistance during the lifetime of the field they are producing from. Understanding the potential of a developing field, therefore, relies on the artificial lift method to be selected. In order to determine the proper method, one needs to combine the related knowledge and experience with the present conditions of the well and review similar cases in the neighbouring fields as well as consider production expectations, initial and operating costs, geographic location and environmental concerns, availability and adaptability of the method, reliability and mean time between failures.

When it comes to the selection criteria, different artificial lift methods show a strong competitiveness in terms of profitability and performance. Hence, not only the aforementioned factors play a role in the lift method selection, other aspects such as fluid properties, fluid rate, depth of the well, downhole temperature and many other come across as defining.

The typical artificial lift forms currently in use in the industry are sucker rod pumps (SRPs), electric submersible pumps (ESPs), reciprocating and jet hydraulic pumps, gas lift and progressive cavity pumps (PCPs). From around 2 million oil wells operating around the globe, more than 1 million use a type of artificial lift. Within this category, more than 750,000 of these wells use sucker rod pumps. For instance, approximately 80% of the oil wells in the US are stripper wells which produce less than 10 BPD with a high percentage of water-cut, for which sucker rod pumping is the most suitable lift method. The statistics clearly indicate the dominance of rod pumping in onshore operations whereas in offshore wells ESPs and gas lift is more popular [1].

Based on their applicability, pumping units can be beneficial in a variety of operating conditions. A list of such diversities can be seen in Table 1:

	SRP	ESP	PCP	Gas Lift	Hydraulic Jet Pump
Maximum Operating Rate (BPD)	6000	64,000	4500	50,000	20,000
Maximum Operating Depth (TVD in ft.)	16,000	15,000	6000	18,000	15,000
Fluid Gravity (API)	>8	>10	<40	>15	>8
System Efficiency	45-60%	35-60%	50-75%	10-30%	10-30%
Gas Handling	Good if gas anchor is used, poor if >50% free gas	Up to 40% free gas at pump suction can be handled with mixed stages	Poor if pump has to handle free gas	Excellent (reduces the amount of injection gas)	Good/fair if downhole gas separation below pump intake
Temperature	Excellent, up to 290 C	Up to 200 C (special motors and cables)	Up to 220 C (limited due to elastomer)	Maximum 180-200 C	Special materials up to 260-320 C
Offshore	Poor	Good	Poor	Excellent (most common method)	Good
Hole Deviation	Typical 0 to 20	Set in section with 0-2° of maximum deviation	Poor (wear & load problems)	Typical 0 to 50	Typical 0 to 20
Noise Level	Moderate	Very low	Low	Low (noisy at compressor)	Low

Table 1. A Comparison between Different Artificial Lift Methods [2]

2.2 Sucker Rod Pumping

Sucker rod pumping systems are the most common type of artificial lift worldwide. These systems can be put to operation for low producing wells as they are the most cost-effective type. Moreover, the long history of using such pumps is the main reason why the wellsite operators are often familiar with the functionality of this system, the maintenance is more convenient and the efficiency of the processes are high. SRPs are designed to lift moderate volumes from shallow depths or small volumes from intermediate depths [1].

A sucker rod pumping unit consists of various components, some of which located inside the well and others reside above the ground. The main parts of the surface unit include a prime mover which is often an electric motor, brakes, gear reducer, counter-weights, a (walking) beam and a Samson post and most importantly the polished rod. Inside the well and right below the polished rod, several sucker rods are connected to one another extending down to a properly selected piston pump. A detailed sucker rod pumping assembly can be seen in the Figure 1.

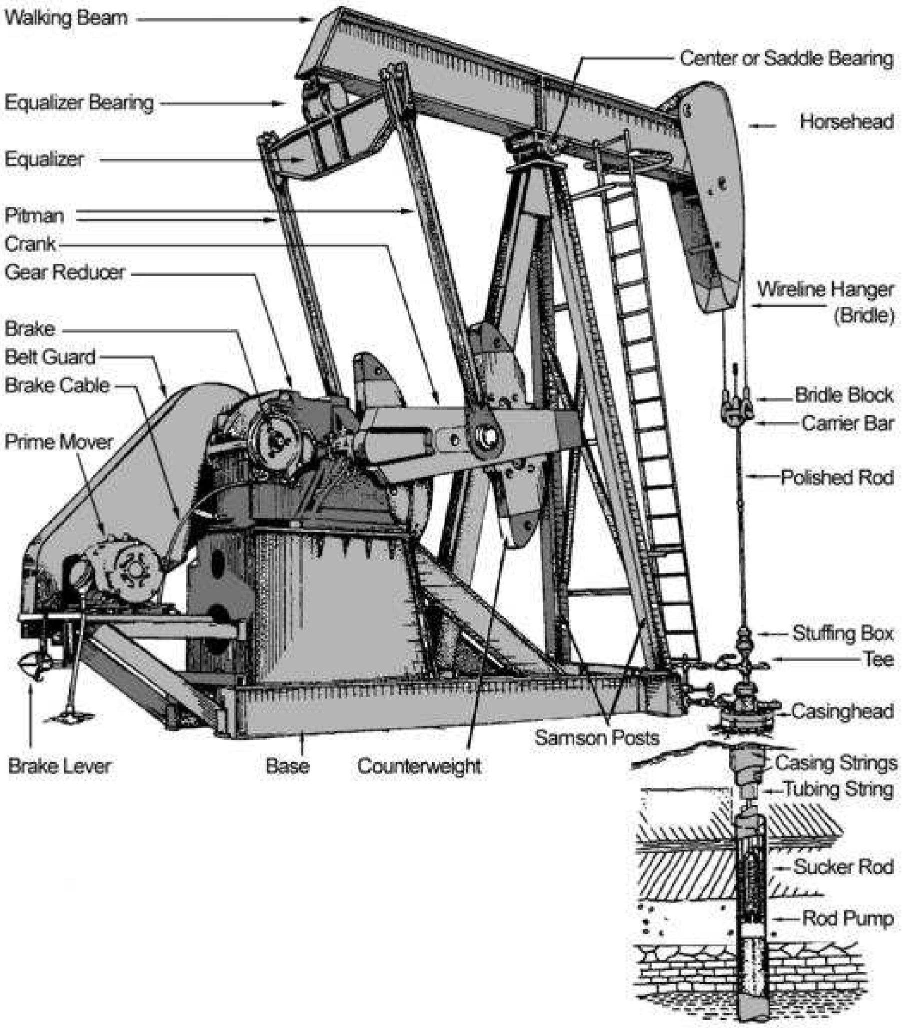


Figure 1. A Typical Sucker Rod Unit [3]

The prime mover creates a reciprocating movement within the walking beam which is balanced by the setup of the counterweights. The motion is further transferred through the rod string to the downhole components, creating an up and down pumping action. Due to the surface installations and their operation method, these systems are also called beam-pumps [3].

The up and down motion of the surface pumping unit will activate the piston in the downhole pump, allowing the entry of the reservoir fluid into the pump cylinder and its discharge to the tubing, above where the pump is located. This volume which in fact has a higher potential pressure is then lifted to the surface [1]. The pump uses two sets of ‘ball and seat’ valves to allow the fluid in and out of the pump barrel, as shown in Figure 2. The stationary valve at the bottom of the barrel is regarded as ‘standing valve’, opened only during the upstroke to suck the fluid into the pump barrel, while the valve located on the plunger is called the ‘travelling valve’, opened only during the downstroke to allow the fluid out of the barrel and into the tubing. These points are highly critical for pump failure analysis since sand production can lead to erosion and shock forces, created by the collision of valves during downstroke if the rod string is elongated, can lead to leakage of the valves and render the pumping operation non-productive.

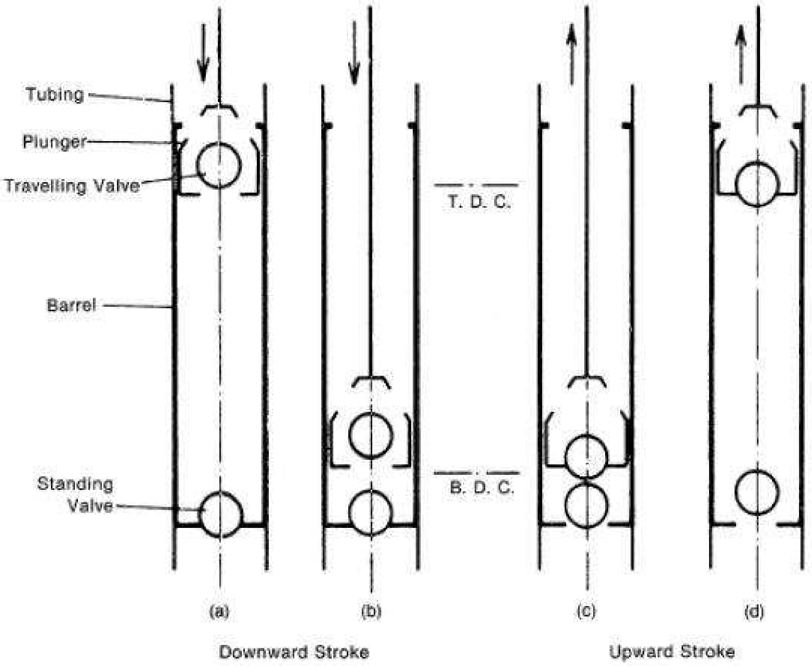


Figure 2. Pumping mechanism in Sucker Rod pumps [4]

Most of the components of a sucker rod pump are standardized by the American Petroleum Institute (API) but alternative components can also be produced by other manufacturers. One of the main components of the system is the sucker rod string which extends from the surface facilities all the way down the hole to where the pump is situated. The string is the constituent which is constantly subjected to cyclic load fatigue and thus many of the failures occur within the length of this structure. The string consists of long steel rods with a diameter between 5/8 to around 1 ¾ in. and with the length of 25 or 30 ft. which are tapered downwards and conventionally screwed to one another with couplings. The details of the design including a failure analysis will be explained in the next section.

Many parameters need to be considered before an appropriate sucker rod system can be chosen. Regardless, sucker rod pumps bring many advantages such as:

- ✓ operation in a wide range of production characteristics
- ✓ applicability to slim-hole and multiple completions
- ✓ adaptability to high temperature and viscous fluids
- ✓ relatively easier corrosion and scale treatments

On the other hand, a sucker rod system can also be restricted due to:

- paraffin formation and scale deposition
- gas locking within the downhole pump
- complications in crooked holes [1]

2.3 Design Criteria

In order to properly design a pumping unit, one needs to understand different factors that can affect the system's performance. In this section, such considerations will be briefly discussed and further, the shortcomings of the conventional systems will be revealed.

2.3.1 Environmental Conditions

In order to design any downhole component, one must consider a variety of parameters that can affect the capabilities of that element. In the petroleum industry factors such as temperature, pressure, salinity and pH value play a critical role in the operation of a system. These factors will be briefly explained below.

Temperature

The key factor in evaluating wellbore temperature is the proximity of the well to the earth's mantle, the relative heat exchange capacities and thermal conductivities of the formation.

Although the geothermal gradient which is defined by the heat-exchange process varies from basin to basin, such variations are small within a specific area. In most hydrocarbon-producing zones, this gradient usually ranges between 1 to 3 °C per 100 m of increase in depth. Nevertheless, in areas where the earth's crust is thinner than average, such as volcanic and geothermal areas, a much higher gradient is expected. A gradient change of about 6 °C per 100 m of depth increase is an example for these zones [5].

A comparison of different gradients is shown in Figure 3.

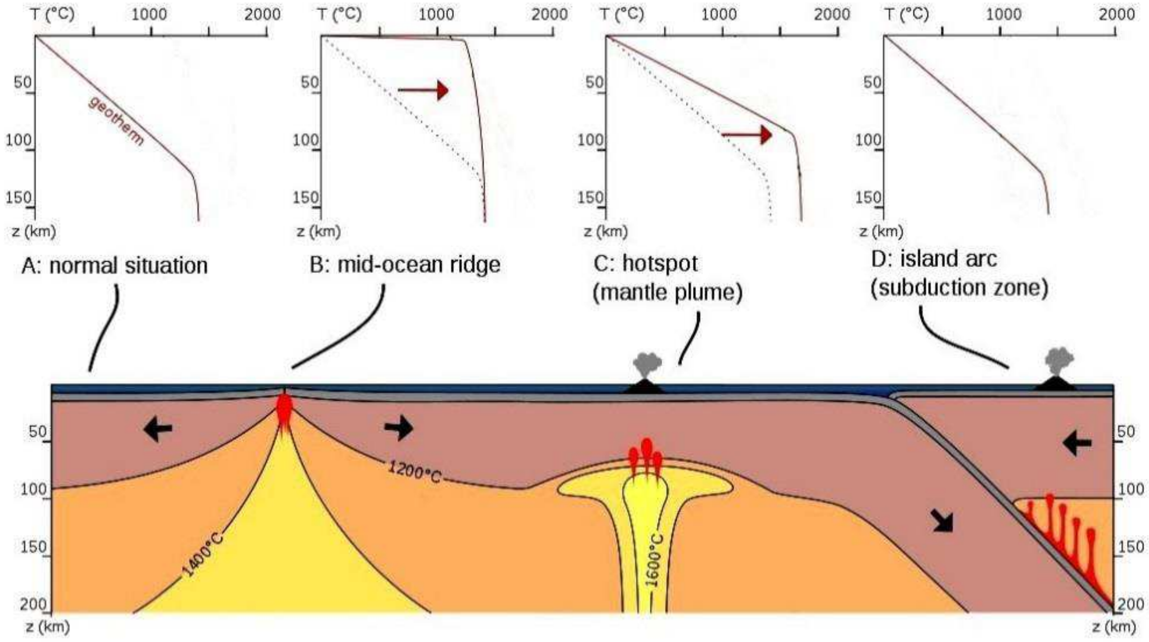


Figure 3. Average geothermal gradients [6]

Pressure

In downhole conditions, the existing pressure is caused by two different factors:

1) *Fluid Hydrostatic* which is related to the fluid density and its depth from surface; and
2) *Effective overburden Pressure* which refers to the pressure or stress imposed on the layer of soil or rock by the weight of the overlaying material.

Pressure gradient is defined as variation in pressure in each unit of depth, often indicated in units of psi/ft or kPa/m. Pressure gradient is not fixed and it can change depending on types of formations as well as salinity level. Generally, the reservoir pressure can range from 1200 psi to 6000 psi [6].

2.3.2 Loads, Stress and Failure Analysis

A collection of loads is to be carefully considered and analysed when designing a sucker rod system. Such loads are generally categorized as either distributed or concentrated and include: self-weight, buoyancy, fluid load on the plunger, dynamic loads resulting from acceleration of the moving masses, frictional forces between liquid/rod and finally mechanical friction between rod/tubing.

Low viscosity fluids have little effect on the load, but as the viscosity approaches 0.01 cp., the load increases rapidly. While specific gravity affects the static load, friction primarily affects the dynamic load [7].

Fatigue failure is the typical failure mechanism of sucker rod strings, occurring at much lower stages of mechanical stresses than the tensile strength or even the yield point and is a result of extremely high cyclic and variable loads. The maximum stress allowed in sucker rod material, or in other words the fatigue endurance limit, guarantees a steady operation for a sufficiently large number of cycles (usually 10 million) under pulsating tension loads typical for pumping operations and can be calculated with the help of modified Goodman formula; "An equation used to quantify the interaction of mean and alternating stresses on the fatigue life of a material" [8] [9]. Some manufacturers use the yield strength of the material instead of the tensile strength for the Goodman diagram safety assumptions. Below, the typical Goodman diagram and the associating formula can be seen in Figure 4:

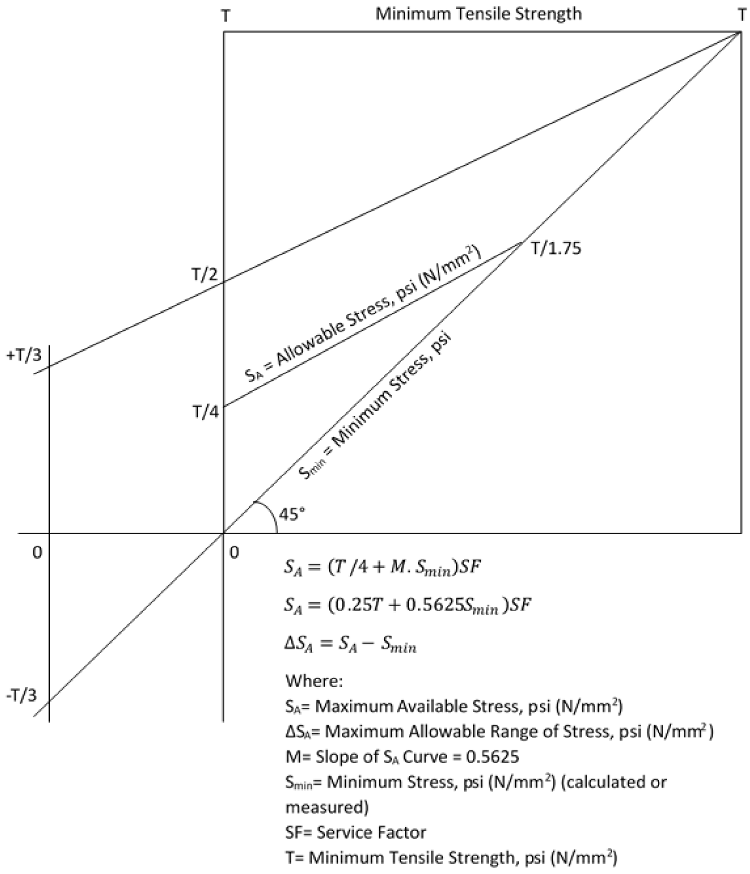


Figure 4. Modified Goodman Diagram [10]

Failures caused by fatigue loading are characterized by two phenomena: 1) initial development of a crack perpendicular to the plane of the load followed by 2) a relatively sudden fracture. Most often the fatigue induced crack initiates at a point of high stress concentration. For steel sucker rods specifically, this point may be a tiny preexistent flaw, an inclusion or a corrosion pit [10].

2.3.2.1 Individual Taper Analysis

A sucker rod string consists of multiple segments with decreasing diameter from surface to the bottom of the well to allow for distribution of load. Each of these segments is called a 'taper'. Number and length of the tapers also play a major role in the design of a sucker rod string. The key factor is the principle to be used for the determination of taper lengths. The main objective is to select tapers that essentially have the same level of safety against fatigue failure. To achieve this goal, one has to use the modified Goodman diagram and select taper lengths so that they have the same service factor values. Since the loads in different tapers cannot be measured during the design process, a calculation of rod loads must be conducted by one of the available methods such as one-dimensional damped wave equation introduced by Gibbs, equivalent safety factor considerations developed by West, modified stress concept introduced by Neely or the latest design procedure proposed by Gault-Takacs which includes force waves reflections in the rod string when calculating rod loads [9].

2.3.2.2 Polished Rod Analysis

It is also essential to consider the polished rod loads during the design procedure. These loads increases exponentially with increasing speed and linearly with increasing stroke length [7]. Studying the motion of the polished rod is hence crucial to achieve a better understanding of the loads. Basically, the motion during the pumping cycle is one of three cases:

1) The well is perfectly counterbalanced and the angular velocity of the crank is constant.
2) The well is insufficiently counterbalanced and the angular velocity of the crank is decreasing in upstroke and increasing on the down-stroke.
3) The well is excessively counterbalanced and the angular velocity of the crank is increasing on the upstroke and decreasing on the down-stroke of the polished rod.

The motion in case 1 approximates simple harmonic motion. Cases 2 and 3 are identified by similar analytical curves divergent in degree only [11].

2.3.3 Problems with Conventional Rods

The idea behind making tapered rods as the sucker-rod string comes from the fact that the weight of the string should be distributed along the length while considering each section's responsibility to carry the weight of the rods below it [9]. Design, construction, attachment and working capacity of individual rods as well as the entire string, as explained in previous sections, is highly affected by material type and applied loads and stresses.

Moreover, stress analysis and failure statistics for different parts of sucker rods proves the weakest point exists within its coupled connections (rod pin and couplings). Hence, it is clear that the fatigue resistance of the connections are inferior to the fatigue resistance of the rod body [12].

These damages can be caused by improper make-up of joints in the field, operation in hostile environment like sour conditions, poor material selection at the manufacturing stage and the formation of the threads inside the couplings [13].

The pie-chart illustrated in Figure 5 shows different sources of failure and proves the critical role of the connection areas in failure analysis:

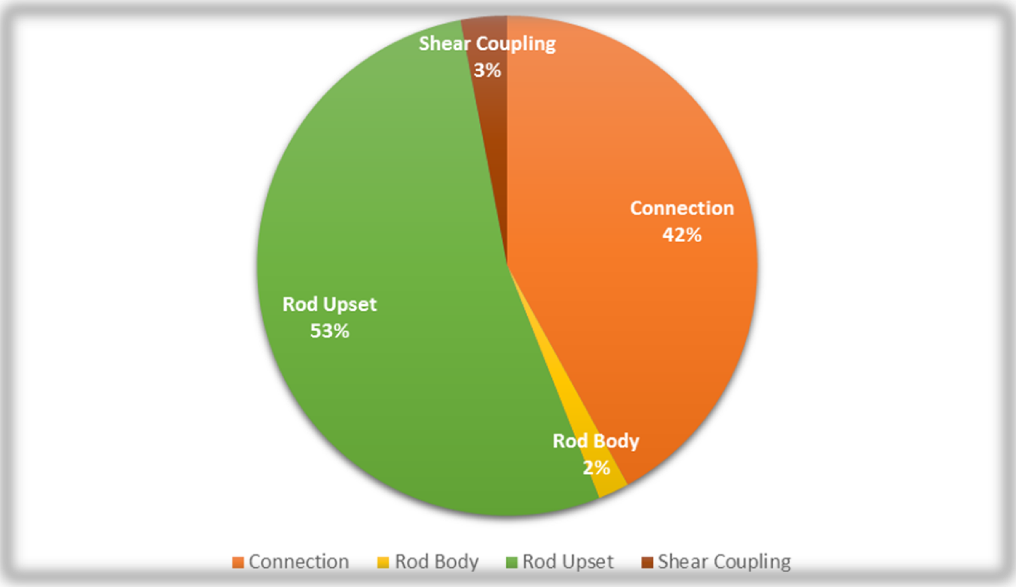
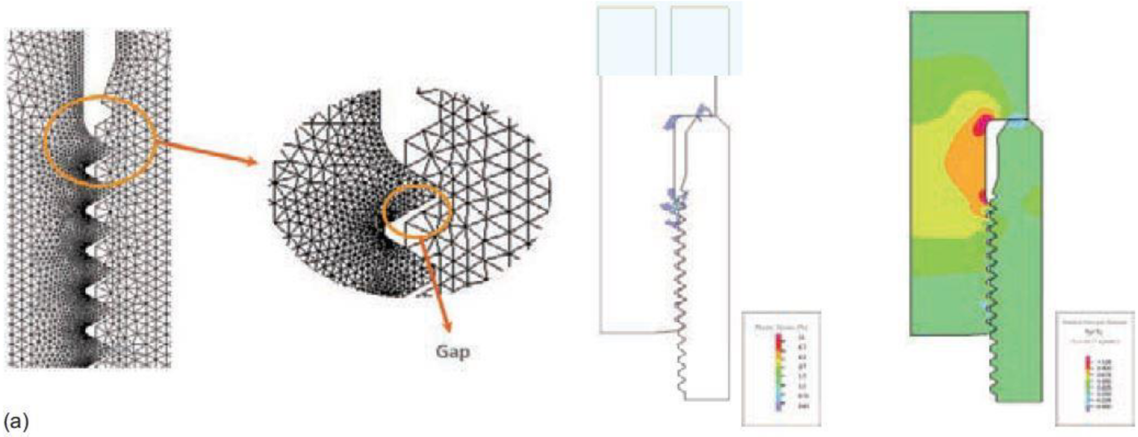


Figure 5. Failure Distribution by Location [14]

Figure 6 also describes various failure mechanisms within the connections:



Loosening tendency (gap between threads)

Permanent deformations in the connection

Stress-concentration areas

Figure 6. Various types of failure at the Couplings [12]

Another issue to consider is the time factor involved in handling and attaching/detaching the rods to form the string and any type of workover operation that would require a completely different setup at the wellsite, pausing regular operations and lowering the production and profits.

As an outcome, a design which can substitute the tapered string with a continuous string with a steady diameter, excluding the existence of couplings will not only allow minimizing fatigue failures, it also reduces the contact forces resulting from the friction of these auxiliary components with the tubing and automatically reduce wear. This means fewer workover operations and a reduction in the corresponding costs as well.

3 Continuous Rod Technology

Limitations and complications arising from conventional sucker rod systems have motivated companies to come up with alternative strategies to further ease the field operations. Over the years, many researchers have introduced new methods and material to increase the pumping efficiency, many of which include presenting a continuous rod string to optimize the assembly of the sting, movement of the pump and flow of fluids. A few of such innovations include welding the individual rods to obtain a string, facilitating coiled tubing as the production tubing and sucker rod, synthesizing flexible steel alloys without any couplings or manufacturing a high-strength cable that can be reeled in and out of the well in a timely manner. These methods will be briefly described in the following sections.

3.1 Welded Sucker Rods

A number of patents have recommended a type of continuous coiled sucker rod which is assembled in manufacturing plants from a number of steel rods, supplied by a steel mill, using a flash-butt welding machine [15]. The properties of the steel used for any design of sucker rod, whether continuous or conventional sucker rod, depend upon the conditions of the well as well as the pumping system used to produce the well. Furthermore, the design of the continuous sucker rod must be such that it can fit neatly on the transport reel and when required, straightened out into the well without sacrificing the desired properties for the load and environmental conditions of the intended use.

Steel is commonly manufactured to ASTM standard A576 and supplementary requirements S7, S8, S11, S12 and S18 are known to produce suitable sucker rod for most oil and gas applications.

3.1.1 Welding the Connections

The raw coils must be fused together end-to-end to form one continuous sucker rod with the desired length. The ends are usually fused together by welding, which result in heat-affected zones adjacent to the welded area. This causes for treatments to relieve stresses and yielding as a result of the welding process. Without such treatments, the heat-affected zones would be a source of potential weakness which would cause failure of the continuous sucker rod in use [16]. A schematic of the conventional method for manufacturing welded sucker rods can be seen in Figure 7:

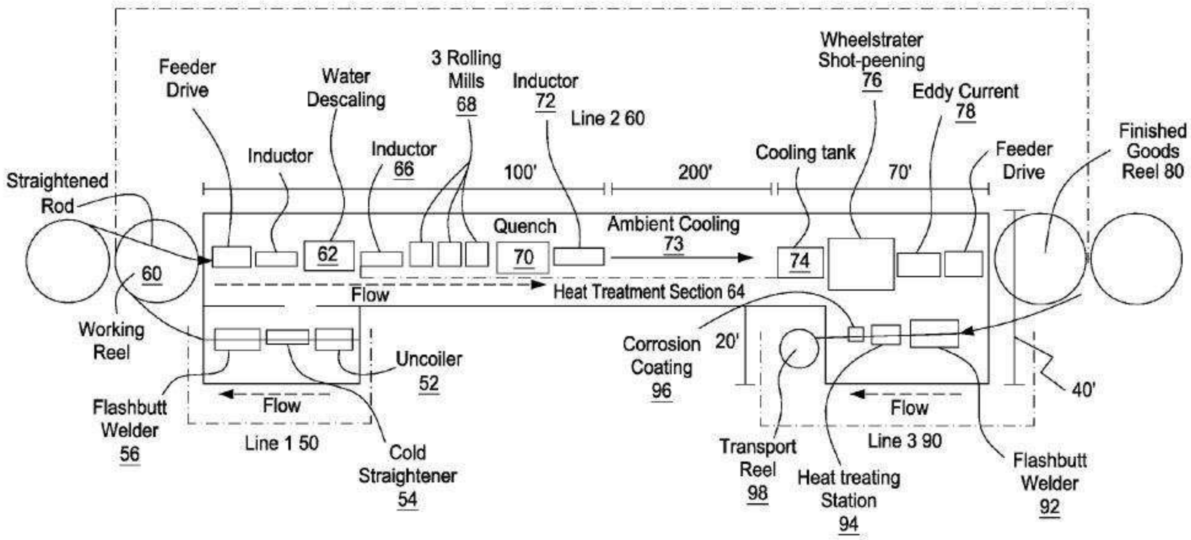


Figure 7. Welded Continuous Sucker Rod Manufacturing [16]

Basically, several methods of joining the continuous coiled sucker rod in the field are available such as mechanical joints or explosive welding and hand welding with portable electrical welding machines etc. One of the most reliable and practical methods of joining a continuous coiled sucker rod is electrical flash-butt welding which can be performed in the field with a truck or a trailer mounted flash-butt welder. This is very much the same method as the one used in a manufacturing plant. The biggest drawback of this method is its huge requirement of electric power, which has to be supplied from many large, heavy and expensive batteries. These batteries need to be recharged very often and their life is limited.

Hence, a special gas pressure welding method is developed for welding parts of a coiled sucker rod in the field. In this method the butted sections of the sucker rod are subjected to heat and pressure to form a weld. The method allows use of a light portable welding apparatus which is much smaller and less expensive than the heavy flash-butt welding machines used for the welding of coiled sucker rod in the field at the present time [15].

3.1.2 Design and Handling

In order to have sufficient strength, the rod string usually requires a tensile strength of 110 ksi, which corresponds to a Rockwell hardness value of around 26 HRC. To rod manufacturers this hardness is a maximum because H_2S corrosion rates typically tend to accelerate above this value. Heat treating the steel is therefore a must in the present day processes for producing such continuous sucker rod.

Welded sucker rod strings are mostly rolled to a semi elliptical shape since round rods produce much higher bending stresses when stored in similar reels. The elliptical shape helps eliminate excessive bending stresses in the rod string when it is compressed into a storage reel which is somewhere around 18 ft in diameter [17].

Although recent methods developed have reduced the capital investment by fusing the rods together with a portable plant at the well site itself, they can be disadvantageous in that they are highly labour-intensive, especially at remote locations.

Issues like this call for a method of manufacturing continuous sucker rods that reduces the number of treatment steps required to be performed while avoid sacrificing essential properties required to make the rod suitable for the purpose of any project. It would also be preferable to have a method which permits reduction of capital investment in equipment and facilities, thereby reducing costs [16].

3.2 Coiled Tubing as a Sucker Rod

Coiled-Tubing (CT) continues to evolve as an enabling technology that provides economical and time efficient operations in the oil and gas industry. It is continuously gaining acceptance due to efforts of the manufacturers, engineers and field operators to improve its capabilities. To date, most CT applications (with the exception of velocity strings) are used when servicing the existing wells and occasionally for permanent production applications.

In 1995, an application of CT was recommended in which CT was used as a permanent production tubing string for artificial lift in shallow, low production wells since pressure losses through small internal diameter was not a restriction. A subsurface pump was designed for this application, and the design was patented (Figure 8).This idea allowed for smaller, less costly holes to be drilled since mostly it is larger hole sizes that are required to be drilled when accommodating sucker-rod and jointed tubing production strings [18].

Furthermore, such a design reduced tubular components needed for the completion as the coiled tubing string acts as both the rod string and the production tubing. It also aids pumping chemicals that will help fluid flow by preventing scale build up and assisting viscosity reduction in case of heavy and viscous oils [19].

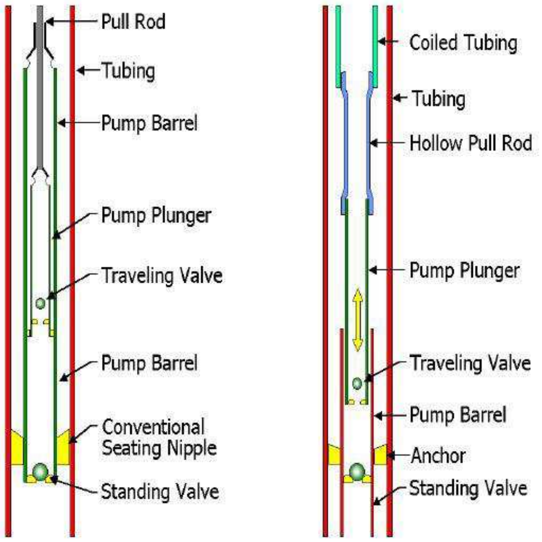


Figure 8. Comparison between a conventional pump (left) and a CT pump (right) [18]

In an assembled system, fluid flowing from each zone goes into the annulus between the casing and the hollow string. With gas being separated and flown to the surface, liquid flows downwards, passing through the side of the anchor to the bottom of the well where they will be lifted with the pump attached to the top of the anchor. So this system allows for separation of the liquid and gas as well as injection of additives or circulation of hot oil treatments. Figure 9 shows a schematic of the downhole system.

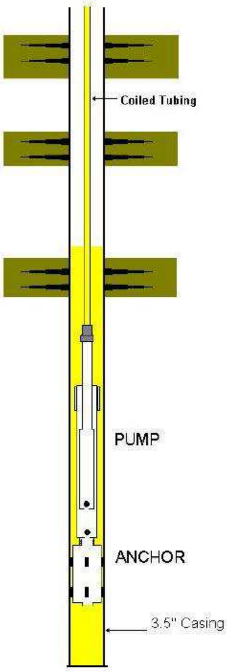


Figure 9. A Typical CT Pumping System [20]

Another consideration in wells using artificial lift is the need for an annular space that collects fluids commingled from different zones and the necessity of such space for segregation of the associated gas. A solution for such producing wells was considered by YPF S.A. in early 1997 and a pilot test was also commissioned. Although a hollow string can pump and convey fluids to the surface, often the unavailability of such rods in the right size calls for another solution and as a result, the idea of using coiled tubing seems more viable [18]. Figure 10 shows such a pump test in Argentina:

Figure 10. CT Pump Test in Argentina [18]

3.2.1 Loads and Fatigue Considerations

Since CT is acting as a completion tubing string, it is subjected to cyclic loads. Hence, the forces caused by temperature, piston effect, ballooning and buckling (mechanical and hydraulic) need to be calculated for a reliable design [19].

Moreover, parameters like tubing elongation caused by the tubing and fluid weight as well as pumping speed, fatigue due to CT reciprocating motion and wear must be carefully considered. Simple calculations can prove that elongation is not a problem at shallow depths if a proper pump and plunger is installed [18].

Compared to sucker rods, coiled tubing has a higher momentum of inertia. Calculations show that, in the zones under compression and while performing downstroke, the buckling in the coiled tubing will significantly less than the one in the sucker rods due to less lateral forces and less friction [20].

Coiled tubing wear should also be thoroughly investigated. Preliminary studies indicate that CT wear is generally not a problem for a 1 to 2-year life span. But more importantly, this problem cannot be well understood without a reliable and accurate wear prediction, which can only be achieved by better wear data gathering through CT pumping operations [18].

Falk[1] suggests the application of API modified Goodman stress diagram used for steel sucker rods to validate that the coiled tubing material would not be overloaded. He assumes

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[1] Artificial Lift Solutions Using Coiled Tubing – SPE 74832

that the coiled tubing material can be compared to the steel used in the rods. A modification should be made to the maximum and minimum stresses to be considered, taking into account the tri-axial nature of stresses. As a result, after all stresses have been calculated, the outcomes should be plotted on a Von Mises diagram to observe the tri-axial behaviour. Later on, modified Goodman diagram should also be used with the difference that instead of T/4, T/2.5 should be used. So the final formula would be like [19]:

$$S_a = (\frac{T}{2.5} + M \times S_{min}) \times SF$$

Since the travelling valve is closed during upstroke, the liquid volume inside the coiled tubing does not change in amount which means that there is no fluid delivery at the surface. However, during downstroke, as the travelling valve opens, a volume of fluid equal to the piston displacement flows into the CT and this means that in such a system, actual production occurs during the downstroke.

3.2.2 Resolving weaknesses

One of the downsides to this design is the reported problems occurred as a result of sand production. To avoid the problems, one has to design:

1) A type of swabbing during completion of the well to consolidate hydraulic fractures and minimize the possible sand production
2) A weak point that should be designed within the CT to facilitate breaking and pulling up the string without breaking the CT in case of stuck pump (e.g. a shear coupling)
3) An appropriate connector between the pump and CT that can be the weak point, also providing rotational restrictions and unscrew the pump when necessary [20].

3.3 Flexible Steel Alloys

Over the years, the vast majority of artificial lift placements have been in vertical oil and gas wells producing from conventional reservoirs. However, in the last years, there has been a dramatic shift to both conventional and unconventional oil and gas production from deviated wells, such as horizontal, S-shaped and slanted wells. Deviated wells have presented a major challenge for artificial lift operations which mainly includes accelerated wear of downhole equipment and tubing. The friction between the tubing and the rod string can wear holes in the tubing, which leads to production delays and costly time-consuming workover operations and equipment replacements.

Service providers have attempted to overcome this problem by modifying lift solutions to meet the specific challenges of deviated wells. As a consequence, continuous flexible sucker rod lift, which deploys a continuous rod of desired alloys with no couplings, has replaced conventional sucker rods in a number of SRP and progressive cavity pumping systems.

Each connection in a traditional sucker rod string introduces a point of possible rod failure. Under- or over-tightening the joints with tongs may promote fatigue failure while manual joint tightening can result in improper make-up torque. A conventional rod also increases safety risks because two dedicated rig hands are required on the floor at all times during make-up and breakout. Therefore, flexible continuous rods are a beneficial alternative primarily due to absence of these threaded connections since they require only two threaded connections—one at the top and one at the bottom of the string—which significantly speeds up overall string deployment.

A sketch of the deployment of such a string called COROD, manufactured by Weatherford, can be viewed in the Figure 11:

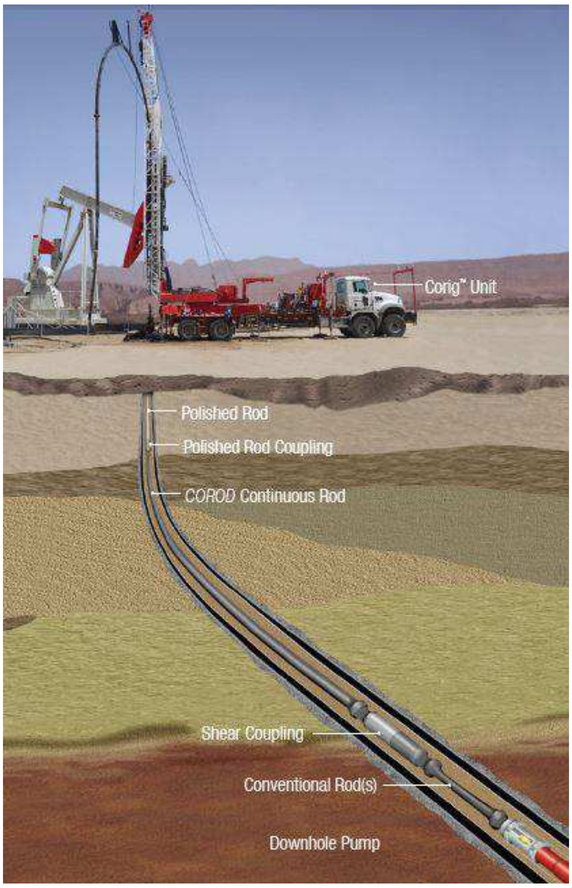


Figure 11. Deployment of a Continuous String by Weatherford [21]

3.3.1 Uniform Body Design

The uniform body design of these continuous rod strings yields three major benefits:

First, the uniform design helps reduce contact loads between the tubing and the rod as the rod moves up and down during pumping [22]. Contact load is defined as the force exerted over the rod string as an effect of contact between the rod string and the tubing. Contact load highly depends on rod string type, geometry of the well, well deviation, rod tension and distribution of the contact between rod string and tubing. Although the conventional rod string with spin-through type centralizers reduces the contact area of the tubing with the coupling (and thus tubing wear), it maintains the contact load (Figure 12) [23]. So the application of the continuous rod helps not to create concentrated sites of wear. Instead, it distributes the contact load evenly across the entire tubing. This dramatically reduces wear rates and extends the run life of the entire system, which means fewer interventions and a longer lifespan for the assembly.

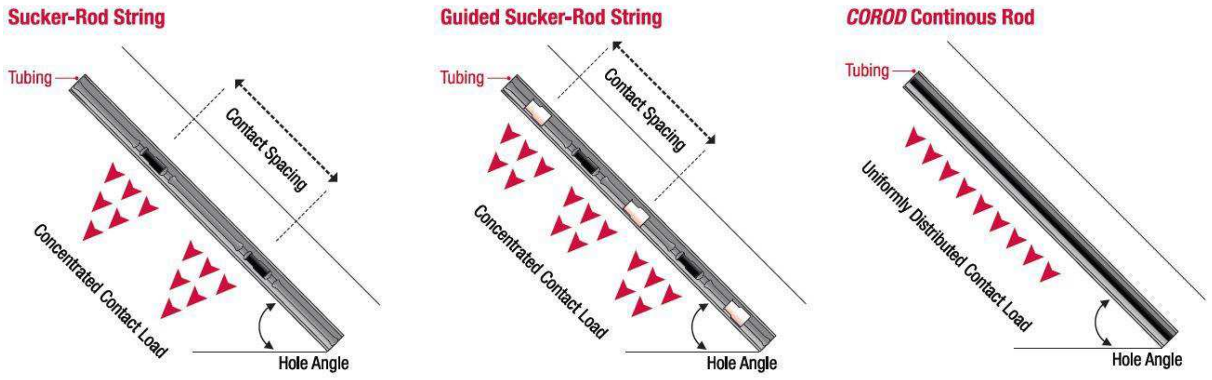


Figure 12. Comparison of Contact Loads [21]

Second, the uniform body design creates a larger annular clearance between the rod string and production tubing, reducing pressure losses and potentially increasing production without changing the surface equipment (Figure 13). It also ensures that the flow of the fluid is laminar, compared with the turbulent flow that arises in traditional sucker rod strings due to the existence of couplings. The elimination of couplings and centralizers also increases overall system efficiency and reduces the corresponding costs.


COROD Continuous Rod

Sucker Rod with Slim-Hole Coupling

Semi-Elliptical *COROD*

Figure 13. Comparison of Annular Space [21]

Third, the uniform body design delivers a continuous string that is up to 8 percent lighter than a sucker rod string of equivalent length. This guarantees less loading on the surface unit and allows operators to deploy the rod farther into the well for improved pumping efficiency.

3.3.2 Reduced Rod Stress

The other benefit of flexible continuous rods as opposed to conventional sucker rods is in terms of rod stress and fatigue. Bending stresses are typically magnified near rod-coupling connections since the coupling is stiffer than the rod body. Moreover, the uniform diameter of a continuous rod provides a rod curvature that is equal to the curvature of the wellbore. This distributes the contact load more uniformly at a bend in the wellbore.

Continuous sucker rod lift systems have been used in conventional oil and gas wells for nearly six decades providing a reliable boost in production with minimal downtime. At the moment, a number of service companies such as Weatherford and PROROD are manufacturing such continuous alloys with various designs to be adaptable to different surface and downhole conditions. Successes such as these are encouraging greater usage of continuous rod lift systems globally [22].

3.4 High-Strength Cable

The first attempt in using a high-strength cable, nowadays known as ‘wire rope’, was carried out in a joint program between E.I. du Pont de Nemours & Co. and Bethlehem Steel Corp. to develop wire-rope pumping units in the 1960s [24]. Pumping with such a cable had been experimented before this date but with limited success as low-strength material with poor abrasion resistance, fatigue, corrosion, incompatibility with well fluids and lack of necessary knowledge and technique had resulted in inevitable failures. In this test, the companies installed a 0.75 in. OD strand made of 37, 0.08 in. wires in a 2800 ft. deep well in 1965. A nylon coating protected the wires from corrosion [25]. More details of the design can be seen in Table 2. The schematic of the strand can be viewed in Figure 14:

No. of Wires	*Wire Diameter [in.]*	*Wire min. Tensile Strength [psi]*	*Breaking Strength of the Strand [lb]*	*Overall Diameter [in.]*	*Well Depth [ft.]*
37	0.08	240,000	42,000	0.750	2800

Table 2. Properties of the High-Strength Cable [25]

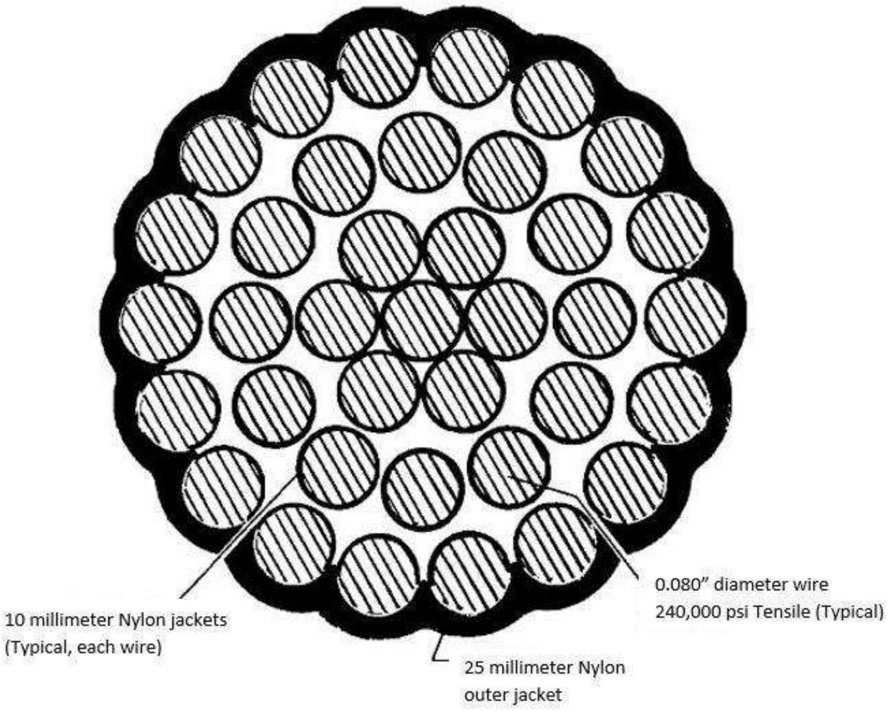


Figure 14. A Cross-Section of the Strand [25]

The first nylon-jacketed high-strength cable (also known as FSR or Flexible Sucker Rod) was installed in Los Angeles Basin well late in 1965. Subsequent installations bring the total number of FSRs in the test program to seven [25].

Another report on high-strength cables replacing sucker rods was from Russia which was carried out by the end of 1970s where a closed-type wire rope was used with an appropriate three-series differential deep-well pump, developed specifically for this application. A successful 2-month operation was reported for one installation in a well with the pump setting depth of 1018 m.

A fundamental research on high-strength cable replacing sucker rods initiated at the University of Petroleum in China in the early 1990s. After 1996, in cooperation with the Qinghai and Zhongyuan oil fields and several iron and steel works, research started on the application of a full-locked coil rope in the oil field. Eventually in 1997, the wire rope was successfully run into a setting depth of 1450 m. in Gasikule oil field. By 2000, high-strength cables had been installed in 20 wells in six Chinese oil fields [24].

A sample FSR setup carried out in the US can be seen in Figure 15:

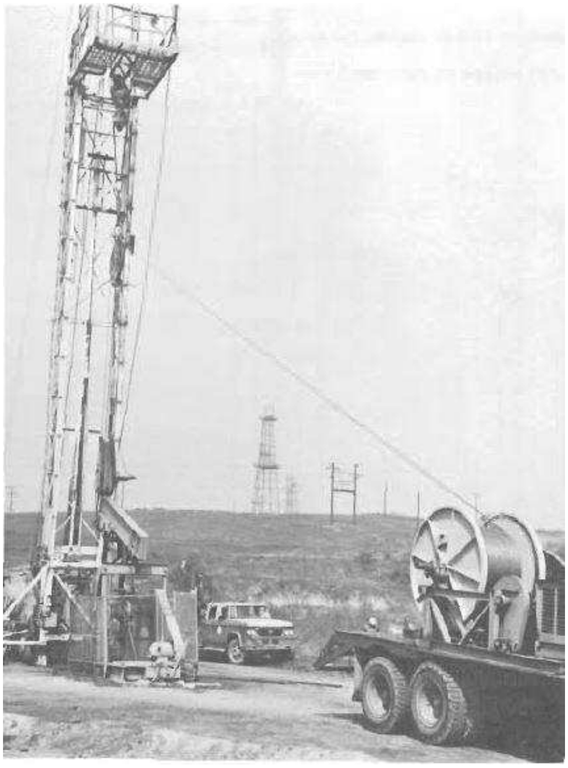


Figure 15. Arrangement of Equipment for Running and Pulling FSR [25]

3.4.1 Design and Benefits

To plan a beneficial project, three test phases must be conducted which include:

- *Determination of feasibility:* converting selected wells with no prior history of operating problems from conventional sucker rods to flexible cables

- *Determination of operating limitations:* installing high-strength cables in wells with histories of excessive conventional sucker rod failures
- *Evaluation of all economics involved* [25]

Application of flexible high-strength cables has various advantages in comparison to the conventional coupled rod strings. For instance, the wire rope's density is 18.5% less than an equivalent steel sucker rod (with the same diameter) which reduces the maximum load on landing by about 18.5%. Measured values in the oil field indicate a 20-30% reduction.

In addition, the smaller difference between the maximum and the minimum load decreases the crank torque, resulting in lower power costs for the pumping unit.

As sucker rods travel, they create vibrations and variable acceleration. This will displace the pump plunger travel on the up and down stroke; Meaning at the top dead centre, the sucker rod will continue to go upwards because of inertia. Likewise, at the lower dead centre, the sucker rod will continue to go downward for the same reason. This phenomenon is defined as over-travel or over-stroke. On the other hand, the cable stroke is longer than that for steel sucker rods, resulting in a higher stroke efficiency. This is one of the main reasons why wire-rope pumping units have more output and higher pump efficiency than steel sucker rod units.

Moreover, these cables have a smooth surface and use only two connections (one at the surface and one near the pump downhole) as opposed to using several couplings. As a consequence, the piston-effect and paraffin problems on the cable surface are minimized. [24].

A comparison of some of these properties with a conventional sucker rod can be seen in Table 3:

	Modulus of Elasticity [psi]	**Total cross-sectional srea [sq. in.]**	**Weight per foot [lb]**
Cable (Wire Strand)	24e6	0.186	0.728
¾ in. CSR	29e6	0.442	>1.4

Table 3. Comparison of Conventional SR and Cable SR [25]

3.4.2 Main problems

Although high-strength cables bring a number of significant advantages, some problems still persist:

- Wire-rope connections can sometimes loosen
- Stroke efficiency can be difficult to improve in conventional pumps because of lower elastic modulus that can cause the cable to stretch and reduce the stroke length

- Wire-rope protective coatings can be a point of failure because of deficiencies in the adhesion strength between the coating and wire rope. In case of coating removal, a prolonged exposure in oil can result in fractures in the wire rope [24].

4 Wire Ropes

The idea of using a continuous rod string has already been explained in Chapter 3. These technologies are becoming more and more popular since the MTBF shows significant improvement, mainly due to the omission of couplings as a linkage and the highest point of structural weakness. From the four different designs which came up during the literature review procedure, the application of wire ropes was chosen for further investigation and modification and from now on will be the main focus of this project. Apart from having all the properties of steel rods, a rope consisting of steel wires is significantly superior to regular rod strings due to the ease of transportation and deployment. The methodology defined by Hood (1968) has since been developed by a number of companies in different countries.

Hence it is important to start off by introducing the concept of wire ropes, their types and specifications and later their compatibility in different forms. By the end of this chapter, a novel design of a wire rope developed by Voestalpine AG in Austria will be introduced and later simulated as part of this project.

4.1 Definition of Wire Rope

“Wire rope is a type of cable which consists of several strands of metal wire laid (twisted) into a helix”. Although in many cases the term cable is used interchangeably with wire rope, in principle wire rope is the name given to the category with diameters larger than 3/8 in. (9.52 mm).

Wire ropes are consisted of strands of wires. While wrought iron wires used to have more popularity, steel is the main material in manufacturing wire ropes today. Steel wires are typically made of non-alloy carbon steel with a carbon content of 0.4 to 0.95% [26]. They are usually named in the format of two letters and a number in between. The number indicates the carbon content of the steel in weight percent multiplied by a factor of 100. For example, the steel name C 84 D means the steel has a mean carbon content (C) of 0.84% and is unalloyed (D). Steels with carbon contents as high as 0.86%, including some cementite (Fe_3C) and ferrite, are more suitable for the rope wires [27]. The very high strength of the rope wires allows wire ropes to support large tensile forces and to run over sheaves with relatively small diameters.

The idea of creating wire ropes came from the concept of iron chains. But as their record of mechanical failure in chain links or solid steel bars led to catastrophes, the development of wire ropes gained more acceptance since flaws in the wires making up the steel cable were certainly less critical as the other wires could easily take up the load. Friction between the individual wires and strands, as a consequence of their twist, could also further compensate for any type of failure [26].

Figure 16 shows a typical rope and its constituents:

Figure 16. A typical wire rope [28]

Wire ropes are vastly used in different industries, primarily for their dynamic behaviour during lifting and hoisting in cranes and elevators, and furthermore for transmission of mechanical power. Static wire ropes are another group which are used to support structures such as suspension bridges or to support towers [26].

In the oil and gas industry, aside from sucker rod string installations, wire ropes are employed as tough drilling lines, geophysical cables, offshore mooring ropes and electromechanical cables that allow for exploration and extraction of oil and gas resources buried deep beneath the earth’s surface [29].

4.2 Construction

Based on the arrangement of strands in the rope there can be a variety of wire rope designs. The most common types are explained as follows.

4.2.1 Spiral Ropes

A spiral strand is the assembly of a number of wire layers helically laid on one another with a common axis, while at least one layer of wire laid in the opposite direction to that of the outer layer [27]. When it comes to spiral ropes, several spiral strands in one or more helical layers come together on a central core. The ropes can either be manufactured with fibre or steel cores, which highly depends on the purpose of the rope in the end [30]. Figure 17 shows typical cross-sections of spiral strand wire ropes:

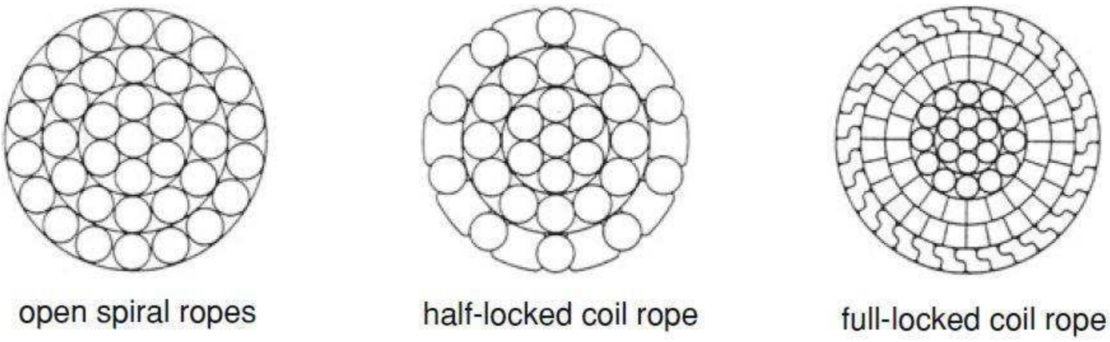

open spiral ropes
half-locked coil rope
full-locked coil rope

Figure 17. A typical spiral strand ropes’ cross-section [27]

Open spiral ropes are made only of round wires and are mostly used as stay ropes for simple purposes. Half-locked and full-locked coil ropes on the other hand have the advantage that their design prevents the penetration of dirt and water and avoids the loss of lubricant. But the most important quality of such ropes is that the ends of a broken outer wire will not leave the rope if they have been constructed in proper dimensions [27].

4.2.2 Non-Rotating Ropes

“The non-rotating ropes are composed of two or more layers of strands that are stranded with alternated lay direction so as to reduce the rotation” [28]. Spiral ropes can be designed and dimensioned in a way that would make them non-rotating, meaning that under tension the rope torque is almost zero [26]. The term “non-rotating” is a relative value since an ideal non-rotating strand does not exist in reality [30]. Figure 18 demonstrates the cross section of some non-rotating ropes:

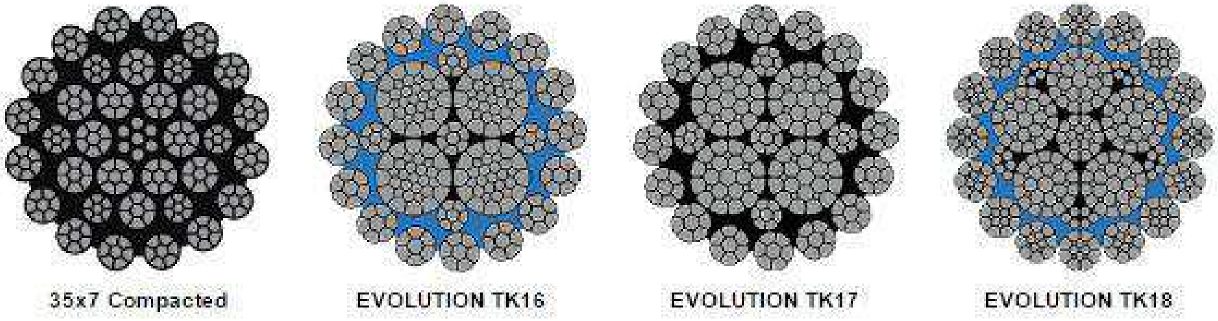

35x7 Compacted
EVOLUTION TK16
EVOLUTION TK17
EVOLUTION TK18

Figure 18. Non-rotating ropes [31]

4.2.3 Stranded Ropes

This type of wire rope represents an assembly of several strands laid helically in one or more layers around a core. This core can be one of three kinds:

1) Fibre core, which is made up of synthetic material. Such cores are the most flexible and elastic, but on the other hand can get crushed very easily.

2) Wire strand core, which is made up of an additional strand of wire. This core type is most commonly used for suspension.
3) Independent wire rope core (IWRC), which is the most durable in all types of environments.

Most ropes only have one strand layer over the core. The lay direction of the strands in the rope can be either to the right (symbol Z) or to the left (symbol S) and similarly the lay direction of the wires can be to the right (symbol z) or to the left (symbol s). The kind of rope where the lay direction of the wires in the outer strands is in the opposite direction to the lay of the outer strands themselves is called “ordinary lay rope”. If both the wires in the outer strands and the outer strands themselves have the same lay direction, the rope is called a “Lang lay rope” (formerly Albert’s lay or Lang’s lay) [26].

Lang’s lay ropes have greater abrasion and fatigue resistance when compared to ordinary lay constructions. In applications where rotation or torque is not often a problem, Lang’s lay could be advantageous [30]. Figure 19 and Figure 20 show the ordinary and Lang wire ropes in comparison to one another:

Figure 19. Ordinary lay ropes [28]

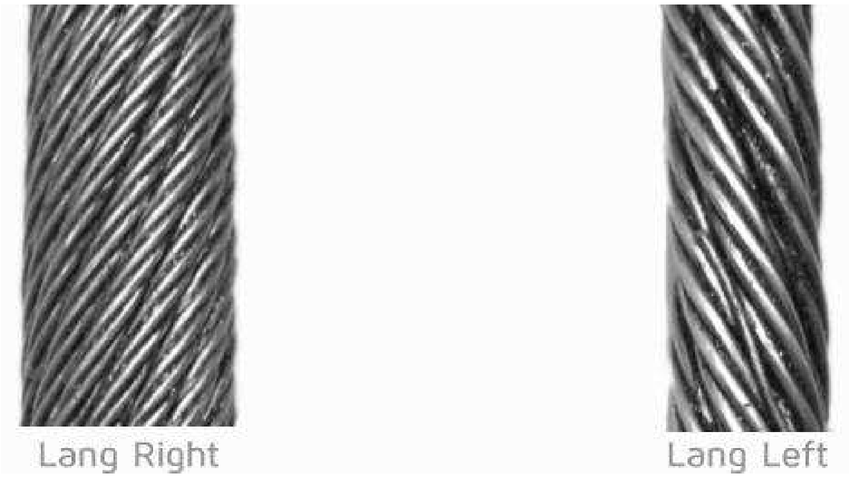


Figure 20. Lang's lay ropes [28]

Multi-strand ropes are in total described as resistant to rotation and have at least two layers of strands laid helically around a centre. The direction of the outer strands in these ropes is opposite to that of the underlying strand layers. Ropes with three strand layers can be nearly non-rotating whereas ropes with two strand layers are mostly just low-rotating [26].

4.2.4 Compact Strand Ropes

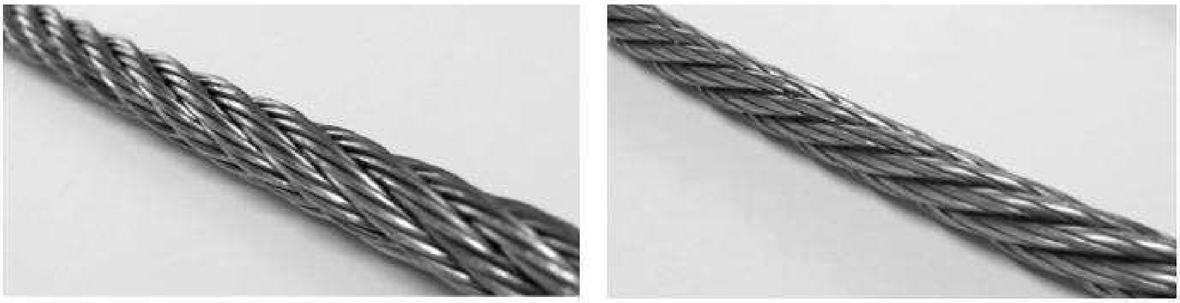
The compaction of strands is a cold deformation process, which consists of reducing the diameter of strand and more specifically its wires by passing them through a die or rollers pairs.

This process generates profound changes in the shape and efficiency of the wires. Such changes include:

- Increase in the metallic cross section of the strand
- Extension of the contact area between the wires
- Smoother strand surface with less permeability
- More uniform distribution of tension on the wires
- More stable strands with respect to the transversal forces

These advantages allow the use of compacted ropes in all sectors and in particular in those applications where high stresses and high load capacity exist [28]. Figure 21 demonstrates the difference between a stranded and a compact wire rope:

STRAND COMPACTED STRAND



STRANDED ROPE COMPACTED STRANDED ROPE

Figure 21. Comparison between stranded and compact strand wire ropes [28]

4.3 Classification

Depending on the type of application, wire ropes have to fulfil different requirements. The main areas of use are:

- *Running ropes (stranded ropes)* that are bent over sheaves and drums. They are therefore under stress mainly due to bending and tension.
- *Stationary ropes or stay ropes (spiral ropes)* that have to carry tensile forces and so are mainly loaded by static and fluctuating tensile stresses. Ropes of this kind used for suspension are often referred to as cables.
- *Track ropes* that have to act as rails for the rollers of cabins or other loads such as cable cranes. Unlike running ropes, track ropes do not take on the curvature of the rollers. Under the rolling conditions, a so-called free bending radius of the rope is defined. This radius increases (and the bending stresses decrease) with the tensile force and decreases with the roller force.
- *Wire rope slings (stranded ropes)* which are used to harness various components. These slings are primarily stressed by bending stresses and afterwards by the tensile forces when bent over the more or less sharp edges of the goods.

It is worthy to note that the rope life is finite and the safety inspections are generally given by detection of wire breaks on a reference rope length, loss of cross-section and any other failures so that the wire rope can be replaced before a dangerous situation occurs [26].

4.4 Design Considerations

Cable design and manufacture is believed to be more like an art than a science. Extrapolation of the typical well-trusted results, meaning a simple scale-up procedure in cable diameter to meet the ever-growing demands for stronger components, is therefore not an acceptable idea and brings out many risks. Although model tests of various designs such as spiral strands and so on can help understanding the concepts but it still falls short when it comes to investigating certain characteristics of the cable. And as factors like fatigue performance require experimentation steps, a full-scale testing could be very costly. As a result, the need for improving a method of cable design which includes exact mathematical methods have been identified by researchers in both academic and industrial establishments [30]. To better simulate the conditions, different factors such as type of coatings, mechanical properties and applied loads need to be fully understood and included in the calculations. The designated softwares will later analyse these input parameters and create the case most similar to the task in hand. The next few sections are therefore dedicated to describe these factors to more details.

4.4.1 Metallic Coating

Rope wires are normally coated with zinc to be protected against corrosion. Zinc coatings are among the most reliable forms of protection because even if the coating layer is partially damaged, the steel remains safe from corrosion as the electro-chemical process corrodes zinc first.

The process is usually done in the form of ‘hot zincing’ or in a ‘galvanizing’ process. In the former, the outer layer consists of pure zinc. Between this layer and the actual steel there is a boundary layer of steel and zinc compound. In the latter, the entire coating layer is very thick and consists solely of pure zinc which as a result creates a smooth surface.

It is important to know that during hot zincing, the strength of the wires can be reduced. Due to this and the fact that suck coatings create a rough surface, the wires are usually recommended to be drawn again. Drawing will increase the strength of the wire again and softens the surface. Therefore, the initial zinc layer is required to be thicker as part of the zinc can be lost during the drawing process.

4.4.2 Corrosion Resistant Wires

In special cases, corrosion resistant wires (stainless steel) can be used as components of the wire rope. Since corrosion resistant wires have an austenite structure, they are not able to be magnetised. This means that the effective testing and inspection methods including magnets are no longer valid for these ropes. It is also proven that these steels are not corrosion resistant in all environments. Moreover, such wire ropes when running over sheaves are not as durable as the ropes made of non-alloy carbon steel.

4.4.3 Lubrication

Wire ropes are bent continuously and this makes wires and the strands to move against each other. Relative movements also take place in wires of stranded ropes, changing their tensile forces by friction. In addition, movements between wire ropes and sheaves in most cases especially when side deflection exists that cause significant friction in time.

The purpose of lubrication is to minimize this friction between wires and strands and between wire ropes and sheaves. This allows for reduction in the wear and also friction-induced secondary tensile stresses. Müller (1996) performed bending tests with lubricated and non-lubricated ropes and the results showed that the endurance of the non-lubricated rope is only 15-20% of that reached by the lubricated rope.

Use of lubricants does not prevent corrosion; hence the zinc coatings must also be applied prior to lubrication. Lubricants must be very adhesive, meaning that they must move back to the contact points if displaced momentarily by pressing. Furthermore, they must have sufficient viscosity so that they wouldn’t be centrifuged away from the rope during movements, specifically around sheaves. They should not contain water or acids either. Several tests have now proven that Vaseline or mineral oil with high viscosity have been proven effective for this purpose.

4.4.4 Poisson Ratio

The Poisson ratio (also known as transverse contraction ratio) for steel is 0.3 but this value can also be used for the steel wires within a strand. As the length-related radial force between the wires is quite small, the reduction of the wire diameter and winding radius in the spiral ropes and in the strands of the standard ropes are only caused by the elongation of the wires. This is particularly true for parallel lay ropes.

Furthermore, the transverse contraction ratio of the strand in stranded ropes is not so easy to estimate. For wire ropes with a fibre core, this ‘‘Poisson ratio’’ is in fact very large. Overall, the influence of the Poisson ratio of the wires is normally not considerable. For strands, the influence is even more reduced as the total number of wires increase. For instance, for a parallel wire strand with 19 wires, the calculated stress of the outer wires is at highest 2 % more and that of the centre wire 3 % less if the Poisson ratios are neglected.

However, for the sake of accuracy in calculating the additional stresses, the rope elongation or the rope elasticity module, a Poisson ratio of 0.3 can continue to be used for the strands and spiral wire ropes. But this will not be valid for the strand helix (strand axis) in stranded ropes which should be measured and not calculated.

4.4.5 Modulus of Elasticity

Elasticity Modulus explains the elongation behaviour of materials under the effect of mechanical stresses. The elongation of a wire rope, as a result of its structure, depends on elasticity module for wire materials, but at the same time the wire material’s elasticity module describing wire rope elongation differs from the wire elasticity module. This means that the rope stress-extension curve is not linear. Therefore, for a certain wire rope, the wire rope elasticity module is not constant but depends on the tensile stresses applied to the rope.

However, as far as strands and spiral ropes are concerned, there is only limited nonlinearity involved which can be neglected in most cases and the wire rope elasticity module for these ropes can be calculated approximately using analytical methods, but this cannot be applied to stranded ropes as their rope elasticity modules can only be evaluated by measurements, and due to the non-linear stress extension curve the wire rope elasticity module resulting from these measurements can only be presented after .

4.4.6 Wave and Vibration

If a long wire rope suffers from a shock load, a tensile force wave (strain wave) travels along the wire rope starting from the initial point of impact. The wave velocity is a defining factor in understanding accidents related to wire rope installations. The tensile stress of a wave will be practically doubled as a result of it being reflected from the termination of the rope and it is possible that the wire rope will break if the velocity of the impact is considerably large. For example, the shock load can be applied on the hanging rope by a falling weight with the striking velocity.

Considering the influence of the damping, the amplitude (stress or extension) is continuously reduced and the frequency is somewhat less. The damping of wire ropes with longitudinal vibrations is considerably more for the small mean stress than for the big one. This behaviour originates from the inner rope friction (Andorfer 1983). [27]

4.4.7 Loads and Stresses

Wire ropes are subjected to various dynamic loads such as tension and bending which have to be considered during calculations for fatigue resistance. Additional loads consist of thermal, internal and external pressure, clamping and lateral crushing loads taking place in cables that are driven through traction winches which all in all makes it very complicated to predict a structure's performance [32].

The strength of the wires tends to increase with decrease in their cross-section as a result of drawing. But in the meantime the breaking extension declines as well. The higher the carbon content of the wires, the stronger their structure will become. Although for wires with small diameters (less than 0.8 mm) the tensile strength reaches about 4000 N/mm^2, for thicker wires this value drops down to 2500 N/mm^2. The standard nominal (here meaning 'minimum') strength of rope wires vary between 1370-2450 N/mm^2. An increase of 300 N/mm^2 is often allowed for the load applied to the rope but the real difference is often way smaller [27].

For wire ropes, in general, tensile stresses, bending stresses and contact stresses all come together to create failure within a wire rope. Under low loads, bending stresses are dominant and fatigue cracks develop at the point of maximum bending stress, propagating in the wire cross-section. Yet under high loads failures often are a consequence of cross-wire notching where strand-to-strand or strand-to-core contact forces generate extreme deformation, eventually breaking the wire [33].

4.4.8 Stiffness

For sufficiently small amounts of axial load perturbations which are not able to initiate full inter-wire slippage on their own, the rope will effectively behave as a solid rod with available inter-wire gaps within the structure. This would be the condition for a limiting no-slip regime. For large enough values of range/mean ratio of axial load, however, large sliding will occur at the points where contact happens between neighbouring wires throughout the rope and hence the rope presents its other limit (lower bound) for stiffness coefficients which is referred to as the full-slip effective stiffness. Evidence of other transition between the no-slip and full-slip conditions have also been reported, both theoretically and experimentally.

The inter-wire contact in ropes is significantly more complex than the case of strands and of course depends on the method they have been manufactured and the service life history of the rope. When considering the pattern of inter-wire contacts, apart from the line-contacts between adjacent wires in the wrap direction of strands, the pattern of inter-strand contacts in each layer of the rope must also be carefully analysed [30].

4.5 Rope Termination

The end of a wire rope tends to fray readily, and cannot be easily connected to plant and equipment. There are different ways of securing the ends of wire ropes to prevent fraying [26]. Two of the most common methods will be explained in the next sections:

4.5.1 Mechanical Termination

Mechanical terminations use pressure and friction on the rope elements [34]. They consist of the wedge action of a spike against the wires and the body of the barrel which develops holding power (Figure 22). Typically, the included angle of the barrel interior cone is 60 degrees [35]. Some initial tightening is performed so that the wedge or collet sits and moves on the taper as tension is applied, in order to promote a continuing increase in pressure [34].

A wedge socket termination is useful for wire ropes when the fitting needs to be replaced frequently. The end loop of the wire rope enters a tapered opening in the socket, wrapped around a separate component called the wedge. The arrangement is knocked in place, and load gradually eased onto the rope. As the load increases on the wire rope, the wedge become more secure, gripping the rope tighter [26].

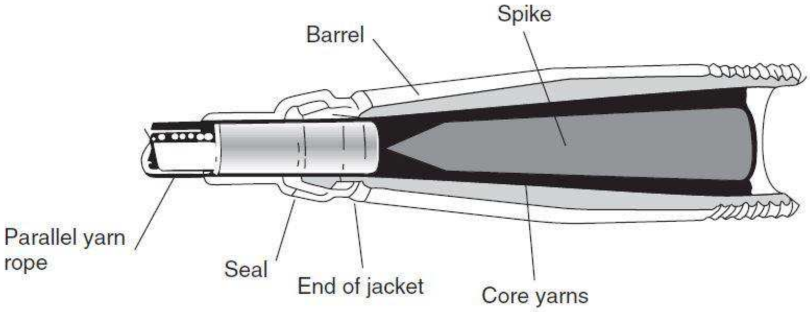


Figure 22. Schematic for parallel yarn rope with extruded jacket [34]

Mechanical fittings tend to be longer in length than an eye splice and thimble (explained later in section 5.4) combination. Nevertheless, they offer more convenient options for interfacing with other fittings or anchor points. In addition, they can be installed quickly without requiring any special skills and most are in fact reusable.

4.5.2 Socketed Terminations

Socketed terminations are commonly used for steel wire ropes, originally made with molten metal but nowadays mostly with resins. These terminations are produced by separating the strands, spreading out the wires and distributing them inside the previously introduced 'conical socket'. The resin (usually a 2-part polyester or epoxy) is later introduced to encapsulate the wires (Figure 23) [34].

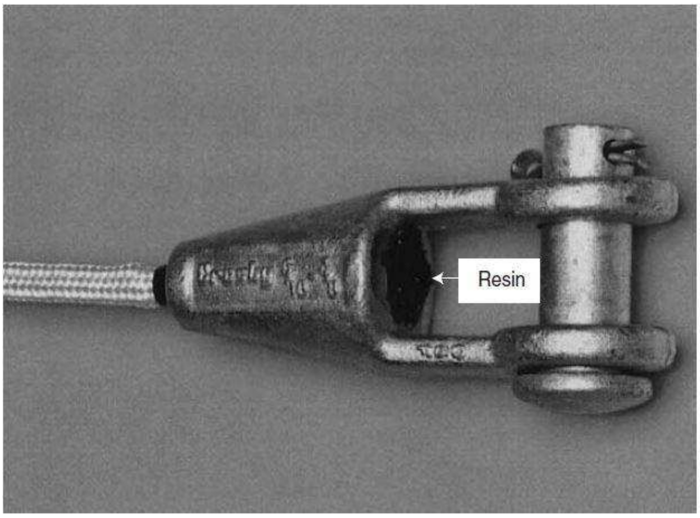


Figure 23. Socketed termination. Socketing resin can be seen at the top of the cone [34]

Of all known terminations, resin sockets exert the least influence on the endurance of wire ropes. Hence, the wire rope breaking force is valid for wire ropes terminated with resin and metal sockets [27].

Producing a socketed termination that will achieve good and predictable results is not an easy process. Any socketed fitting, especially the ones used for critical applications, should undergo a procedure that is proven or verified by prototype testing. Small rope sizes in the range of 12 to 24 mm have shown more success than larger sizes while very large size (over about 60 mm) lacks a good record. Although socketing process can prove to be much easier to understand and employ, even with a reliable socketing design, the fittings would still be quite large and heavy in comparison to a spliced-eye with a thimble. This means that at this point in time, for large ropes in critical applications, the proven reliability of spliced eyes should be considered first [34]. Nevertheless, considering the design of the wire rope used in this study, as will be explained shortly, this method of termination seems to be the most valid and useful.

4.6 Pre-stressed Wire Rope Designed by Voestalpine

The basic aim of pre-stress steel is that it raises both the quality of steel and its resistance to tension and compression.

The steel, therefore, goes under treatment to achieve the desired properties. The following are the treatment processes:

- *Cold working (cold drawing)*: by rolling the bars through a series of dyes. It re-aligns the crystals of the material and increases its strength.
- *Stress relieving*: by heating the strand to about 350°C and then cooling it slowly. This reduces the plastic deformation of the steel after the onset of yielding.
- *Strain tempering for low relaxation*: is being done by heating the strand to about 350°C while it is under tension. This also improves the stress-strain behaviour of the steel by reducing the plastic deformation after the onset of yielding. In addition, the relaxation is reduced.

It is important to use a kind of steel in pre-stressed applications that is of good quality, including the following attributes:

1. High strength
2. Adequate ductility
3. Bendability
4. Low relaxation
5. Minimum corrosion [36].

4.6.1 Mechanical properties

Voestalpine manufactures a number of pre-stressed wire ropes in different diameters. The particular product, chosen for further investigation, is a 15.7 mm stranded non-alloyed carbon steel[1] wire rope consisting of 7 wires, each with a diameter of 5 mm. The rope is covered with a polyethylene jacket with a thickness of 1.5 mm to keep the wires together and protect it against damage. The wires have a zinc coating and are covered with wax to reduce friction between them while movement takes place. The wires are also pre-stressed, which results in the minimization of creep during operations, making it a much better option for sucker rod system's cyclic loading and reciprocating movement.

This rope has been initially designed to withstand the steady load of suspension bridges and is intended to be exposed to normal temperature and pressure environments. They are reeled in lengths of 800 m, 950 m and 1200 m and in spool diameters of less than 1.5 m and can therefore be transported on the back of a truck.

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[1] C82D2 (ISO 16120-4:2011)

Figure 24 shows this wire rope without its cover and Table 4 describes its properties in detail.

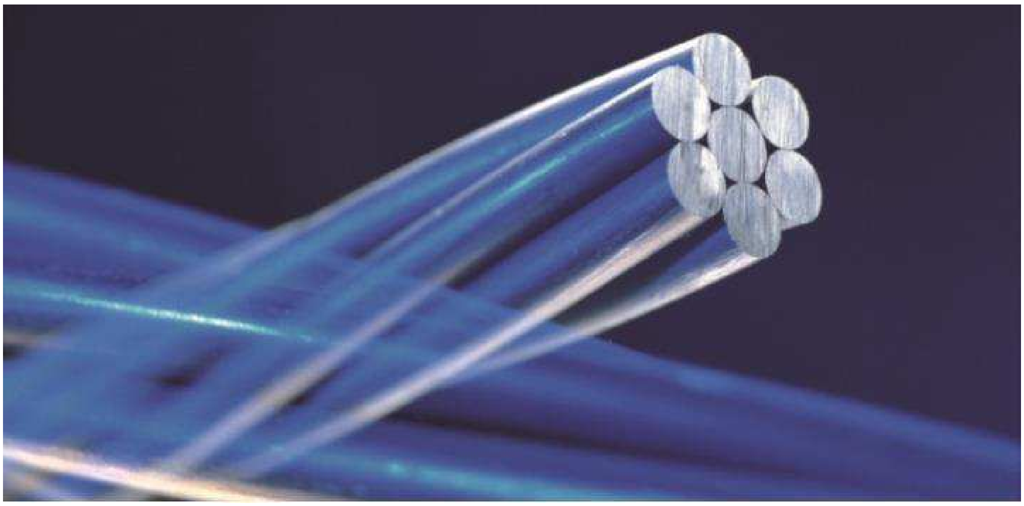

Figure 24. Voestalpine pre-stressed stranded wire rope [37]

Diameter	Density	Poisson ratio	Modulus of Elasticity	Tensile Strength	Cross section area	Mass	Break load	Maximum load at 0.1% elongation	Elongation at break
mm	kg/m³	-	GPa	MPa	mm²	g/m	kN	kN	%
15.7	7.81	0.3	187	1860	150	1172	321	246	>3.5

Table 4. Properties of the Voestalpine stranded wire rope [37]

Voestalpine has also designed a compacted wire rope with slightly different properties listed in Table 5:

Diameter	Tensile Strength	Cross section area	Mass	Break load	Maximum load at 0.1% elongation
mm	MPa	mm²	g/m	kN	kN
15.2	1860	165	1289	353	270

Table 5. Properties of the Voestalpine compacted wire rope

In this case, the wires are covered in fat and are free to move inside the jacket. The advantages of the compacted rope in comparison to the stranded rope are:

1. 18% more cross-section area in comparison to a standard rope with the same outer diameter
2. 10% more break load value in comparison to a standard rope with 150 mm² cross-section as a result of 3% reduction in diameter
3. More effective anchoring, due to higher grip-area of wedges
4. Lower surface tension on the jacket in bends, with application of unbounded tendons [37]

4.6.2 Jacket Cover

Although the steel itself is predicted to resist the harsh wellbore conditions, the synthetic jacket has to be tested for its performance in such environments. The cover has been provided by Sabic Company and is a high-density polyethylene normally used for pipe extrusion. The properties of this jacket can be seen in Table 6:

Density	Carbon content	Total water content	Tensile modulus	Heat deflection temperature (at 1.8 MPa)
kg/m^3	%	ppm	MPa	°C
958	2	50	1000	42

Table 6. Properties of the jacket coating

The heat deflection temperature of this material shows very little resistance to pressure and temperature. In addition, there is no available test data that proves this cover is a proper choice for application in sour environments. Therefore, until higher strength jackets are provided, it is not recommended to use this material in real-life operations.

4.6.3 Corrosion Resistance

A corrosion test has been performed on the wire rope at Voestalpine facilities according to the ISO 15630-3:2010 standard. During this test, the behaviour of the rope was observed under the influence of an aggressive solution containing 99% NH_4SCN and at a temperature of 50°C while being loaded to 80% of its actual tensile strength. In such conditions, the wire rope broke in a matter of hours.

This assessment was carried out under severe environmental conditions and therefore cannot render the wire rope’s performance as insufficient. However, to gain a better understanding of the wire rope’s behaviour, new tests must be conducted to more accurately simulate the wire rope’s response under load scenarios and environmental conditions that are present in the selected wells. Such tests have been discussed and planned and will be performed in the upcoming months.

5 Fibre Ropes

The advancement of steel wire ropes has created a more practical and cost-effective alternative path in various industries where high-strength material and a long lifespan is a necessity. However, the properties of steel are still a concern especially in weight-sensitive applications or in areas where corrosion can be severely troublesome. Such factors call for a more compatible material that is not only lighter but also stronger than the steel wire while implemented in rough operations with cyclic stress. Consequently, the topic of synthetic fibres comes into consideration since they satisfy the aforementioned characteristics and their properties can be enhanced more conveniently in laboratories. This is the main reason why fibre ropes will also be investigated during the course of this project.

High-strength fibre ropes have been gradually introduced into applications which were formerly dominated by traditional steel wire ropes. When strong rayon fibres (regenerated from natural cellulose) became available in the 1930s, their influence on the rope industry was negligible. But what led to major changes in fibre ropes was the invention of the polyamide Nylon 66 by Wallace Carothers. This was a new polymer synthesised from chemicals in coal or oil. As a result, the mid-twentieth century marked the start of the first considerable change in rope fibres since ancient times. Nowadays synthetic fibres dominate the rope industry. Still, for many years, nylon remained the premium rope fibre because of its strength, extensibility and toughness.

The next synthetic fibres to come strongly into rope production were the polyolefins, polyethylene (polythene) and polypropylene, which managed to replace natural fibres in the cheaper, commodity rope market. “Polyester”, also known as “polyethylene terephthalate”, was produced before polypropylene, however its use in ropes mostly presented itself after the development of strong industrial yarns, primarily for tyre-cords. Now polyester has successfully overtaken nylon in high-performance ropes, except for applications where lower elastic modulus (less resistance to extension) or reasonable recovery from high stresses is to be achieved.

The demand for advanced composites with high strength and stiffness called for development of the second generation of synthetic polymer fibres including high-modulus fibres with strengths as high as twice that of nylon and polyester and low break-extensions. Carbon fibres were the first type to be synthesized but at the same time they were too brittle to be useful in ropes with bending characteristics, except possibly as pultruded composite rods, which act similar to steel wires.

Defining Tenacity as ‘the ultimate breaking force of the fibre (in gram-force units) divided by the denier (a measure of the linear density) [38]’, the first high-modulus high-tenacity (HM-HT) synthetic polymer fibre, which became available in the 1970s, was the (para-) aramid fibre, Kevlar®, from DuPont. Since they are made from linear polymer, the aramids would yield under compression and this shows a limitation, but simultaneously has advantages for ropes because the fibres can be severely bent without breaking. The production of aramids continued in the 1980s by the high-modulus polyethylene (HMPE) fibre, Spectra®, from *Allied Fibres*. Twaron® is another para-phenylene-terephthalamide (PPTA fibre) produced by *Teijin* that behaves similar to Kevlar®. Aramid fibres are generically defined as having at least 85% of amide groups joined directly to two aromatic rings. Technora®, which is a fibre also developed by *Teijin*, falls within this definition, but differs in several ways from PPTA fibres such as Kevlar® and Twaron® [34]. Another HMPE fibre available in the industry is Dyneema® developed by *DSM*, which is more specifically an ultra-high molecular weight polyethylene (UHMWPE). Chemical composition of Dyneema® can be seen in Figure 25 and its speceifics will be further described in section 5.5 as part of the project's scope.

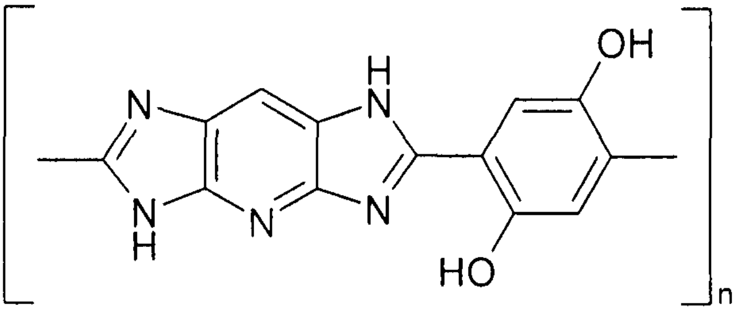

Figure 25. Chemical structure of Dyneema®'s UHMWPE [39]

5.1 Rope Structure

Fibre ropes are defined as almost cylindrical textile bodies with cross-sections that are way smaller compared to their lengths and used as tension members. The rope structure must be capable of controlling large numbers of synthetic fibres in coherent, compact, and flexible configurations, usually to deliver a selected breaking strength and extensibility with the minimum amount of fibres.

In fibre ropes the fibres are commonly arranged in helical structures whose axes form helices in larger structures. This process continues in stages until a rope is complete. The structure will come to form either by laying (twisting) or interlacing (braiding) techniques which arrange and contain the rope elements. Unstructured ropes, or those with very small helix angles, may require enclosure techniques of braided or extruded jackets to hold the elements together.

Rope structures can be divided into two general categories. These are:

1) Laid and braided ropes with properly high twist or braid angles; these are the most common structures for general purpose use. They are found in industrial, marine, recreation and general utility service. Applications cover everything from small cords used to tie-up packages, to large hawsers for mooring tankers, and include clothes-lines, yachting ropes, haul lines for fishing nets, lifting slings, and a variety of other applications. Laid and braided ropes for general purpose uses are constructed as:
    - Three-strand, four-strand and six-strand laid (Figure 26)
    - Eight-strand plaited

- Hollow braid, eight and twelve strand (also called ‘single’ braid) (Figure 27)
- Double braid (also called ‘braid-on-braid’ and ‘2-in-1’ braid)
- Solid braid* (also called ‘parallel braid’)

It is important to note that the terms ‘braided’ and ‘plaited’ are used differently by different authors. Plaited ropes are usually regarded as a sub-set of braids, which produce a distinct form of rope by different rope-making operations to other braided ropes.

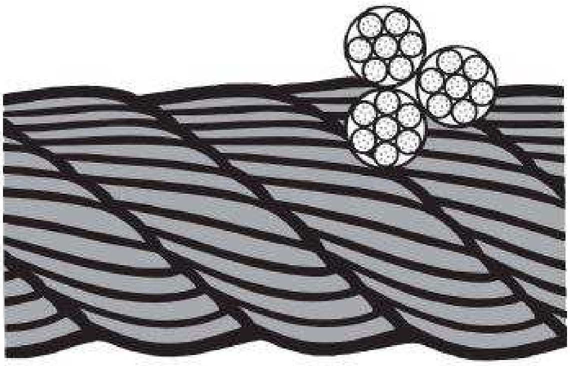

Figure 26. Example of a laid rope with 3 strands [34]

Figure 27. Example of braided ropes [40]

2) Low twist rope structures, designated to specialised and demanding applications where high strength to weight ratios and low extensibility are essential factors. This would include tethers for astronauts, guys for tall masts, deep sea salvage recovery ropes, mooring lines for floating oil platforms, and hoist cables for deep mines. Low twist ropes for such technical uses are designed as:
    - Braided rope with jacket
    - Parallel strand, jacketed (Sometimes called ‘parallel sub-rope’ if the strands that make up the rope are small ropes themselves)

- Parallel yarn (or filament), jacketed
- Kernmantle rope (Quite similar to parallel strand, jacketed or parallel yarn, jacketed but with thin, coloured braided jackets.)
- Wire rope type, exterior surface jacketed
- Wire rope type, each strand jacketed

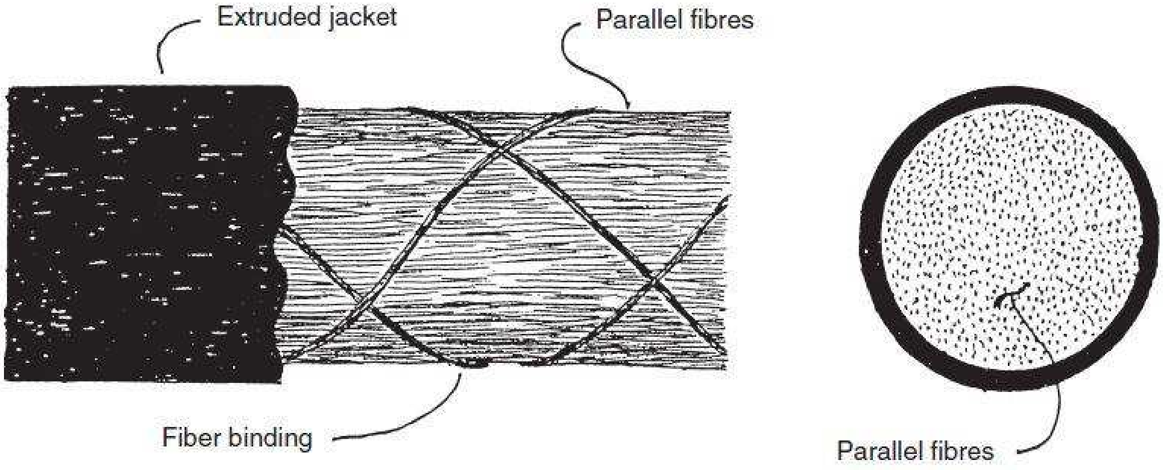

Figure 28. Example of a parallel fibre rope with braided jacket below and extruded jacket above [34]

Obviously there are wide variations within each type of rope structure. As a result, the appearance and behaviour of the structures can be influenced by different factors, a few of them are mentioned below:

- Type and size of fibre material (textile yarns) used
- Dual or blended fibre materials
- Amount of twist at each stage of production
- Size and number of sub-components at each stage of production
- Tension on sub-components during production
- Post-production heat and other treatments

Individual companies have advanced their own technology and rope designs into more of a skill than a science. Personal preference and company history are subjective factors that influence the choice of rope structure, but one of the most important objective factors is the availability of proper production machinery. That’s why for high-performance general-purpose ropes, the range of design variations within any one type of construction can be fairly small. Occasionally, a rope-maker may change the design extensively from a conventional model to meet a particular need. But as names for different rope structures vary throughout the world, there will always be a confusing abundance of trade names.

5.2 Applications

A major change in the wire rope industry happened in the last quarter of the twentieth century with an aim towards more demanding engineering applications. This was triggered by the high strength of the second generation of synthetic fibres, which would categorize them as materials stronger than steel on an area basis and vastly stronger on a weight basis, especially when submerged for mooring applications. Joint industry studies were set up to evaluate ropes for deep-water moorings, which concluded that the modulus of polyester was more suitable for this growing market. Additionally, the HM-HT fibres are expected to find use in deep-water mooring as depths increase. Moreover, they have found important applications in more specialised markets in areas where very high stiffness is required. More details on mooring lines will be explained shortly.

The use of fibre ropes in such demanding engineering applications has become a motivation for change of culture, which contrasts with the old basis of craft experience and trial-and-error. Consequently, for the first time in the history of textile, manufacturers have had to adopt the engineering-design approach, which expects calculations to be done and requires quantitative design data to be specified and predicted. Rope experts were obliged to work with marine consulting engineers to carry out research and accurately predict fibre rope performance in order to provide inputs to mooring analysis computer programs.

In more traditional applications, such as towing and docking, fibre ropes are replacing steel primarily because of their light weight and softness which make for easier and safer handling. This is not only welcomed by crews, but also proves economic for owners. Potential benefits were proven, for example, by Cook et al. (1994) who showed that for a large-span structure, cable weights of aramid would be a quarter of those in steel with considerable overall cost-benefit improvements, but still conservatism often overcomes [34].

Mooring Lines

In Oil and Gas industry, fibre ropes are mostly used as a replacement to conventional mooring lines in offshore applications (Figure 29). For deep-water moorings, weight is a substantial factor. Generally, steel cables were used for catenary moorings, but as depths go beyond 500 metres an increasing fraction of the rope tension is needed to support the weight of the steel line itself. There is a critical length, called the breaking length, under which a material will break under its own weight. For polyester in air, this length is three times greater than for steel and in water it is more than ten times greater. Although the use of improved steels and taking measures such as expensive flotation devices have enabled steel moorings to go to greater depths, the fact that they are difficult to handle and maintain gives way to polyester moorings to be increasingly preferred beyond depths of 1000 metres [34].

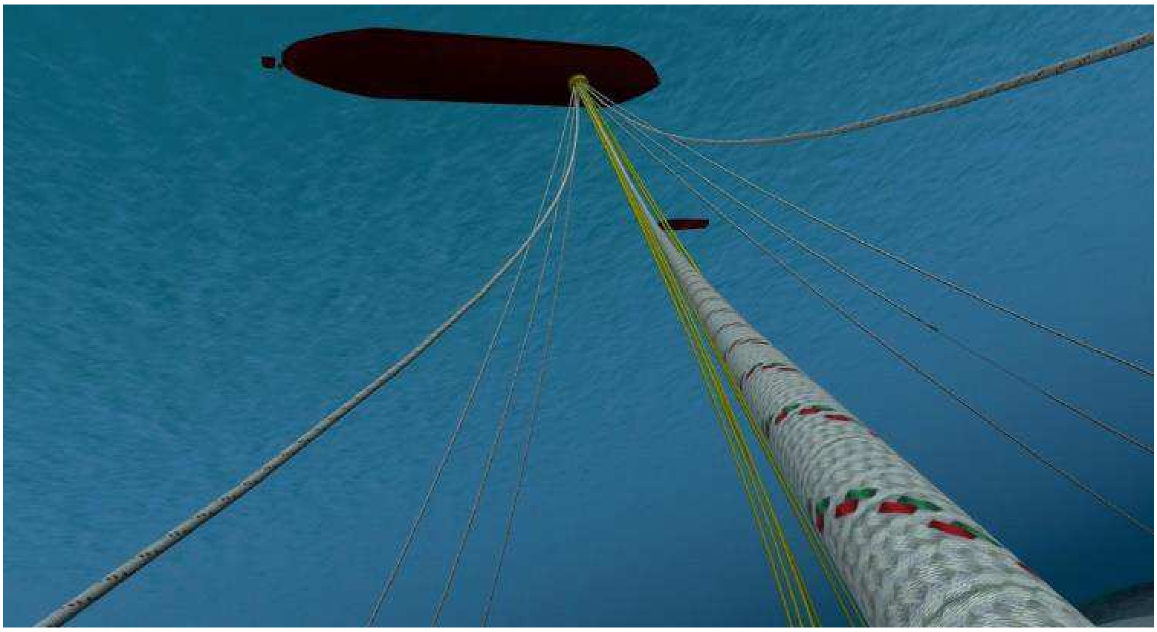

Figure 29. Deepwater mooring ropes (DSM Dyneema®) [41]

5.3 Mechanical Properties

Ropes created out of natural fibres are popular due to flexibility, ease of handling, good gripping surface, knot retention and relatively low recoil energy in case they break. They do not melt, which can be extremely helpful in some applications. The cost per size basis can be relatively low but will vary for strength and longevity. A disadvantage is deterioration of properties as a result of exposure to rough biological and environmental conditions. Natural fibre ropes are still widely used in the world but their tensile properties are significantly inferior to those constructed of synthetic fibres.

Ropes of synthetic fibre are the focus of many projects because of their high strength compared to weight while the metallic alternatives (i.e. wire rope, chain, and rod) are way heavier for the same strength. When submerged in water, fibre ropes lose much of their weight, and some are even buoyant, so the difference becomes even more distinct. In addition, laid, plaited and braided fibre ropes are very flexible. There also exist jacketed fibre ropes which often have higher strengths than conventional types but are less flexible and therefore not used in situations that require frequent handling. However, compared to wire rope of equal strength, almost all fibre ropes can be bent and coiled much more easily.

5.3.1 Stretching

Fibre ropes' ability to slightly stretch under load can be a beneficial characteristic. There can be many situations where shock loading may occur and consequently the elasticity of the rope reduces the peak forces; for example, fall protection in mountaineering. Moreover, objects secured by ropes may move, such as a vessel moored to a quay, and the stretch in the rope provides limited movement without developing large forces, though it is also important to prevent any large movement in order to avoid the build-up of momentum. Ropes used in parallel will also create better load sharing and varying the fibre material or rope construction can produce a wide range of tensile properties, from behaviour near that of wire rope (very stiff) to that of nylon, which can simply stretch over 20% of its length before breaking.

That being said, one disadvantage is that stretch can be quite dangerous in a rope with good elastic recovery because of the energy stored in an elongated rope. If it should break, or the anchorage fail, the recoil can be deadly.

5.3.2 Abrasion and Degradation

Most fibre ropes are not completely resistant to abrasion or cutting in comparison to wire ropes or chains. This can be a limiting factor in their use in many applications. Problems can be overcome with special gear or procedures, but may be impractical as handling could become complicated.

In general, most man-made fibre ropes are resistant to degradation from the environment in which they are normally used. With the wide variety of fibre materials that are available, or with the use of special treatments, chemical, bacterial, fungal and ultraviolet stability can be found for almost any application. This can be an essential and critically useful property if longevity is important or when replacing metallic members that are subject to severe corrosion.

5.3.3 Stress-Strain Behaviour

During the process of rope construction fibres tensile stress–strain behaviour is a controlling factor. These include not only tensile properties (namely extensibility, and its complement extensional stiffness, recovery from loading, creep and other time-dependent effects like energy absorption on impact loading, energy dissipation in the form of heat, break load and break elongation) but also bending and torsional stiffness.

It is important to characterise material properties so the direct measures of load and elongation must be normalised to account for specimen dimensions. Strain and Stress are therefore used for this purpose and are recalled below:

$$Strain = \frac{increase\ in\ length}{original\ test\ length}$$

$$Stress = \frac{force}{area}$$

Although usage varies, stress and strain are preferably defined as a fractions; extension as a percentage; and elongation as an absolute increase in length.

Precise tests need to be carried out to give the most accurate interpretation of a rope’s stress-strain behaviour. The following factors should be considered and controlled in performing tensile tests:

- ✓ Specimen length
- ✓ Rate of extension (or some equivalent factor, such as time-to-break or frequency of cyclic loading)
- ✓ Temperature
- ✓ Relative humidity for moisture-absorbing fibres.

Figure 30 shows the stress-strain behaviour of some fibres in comparison to steel:

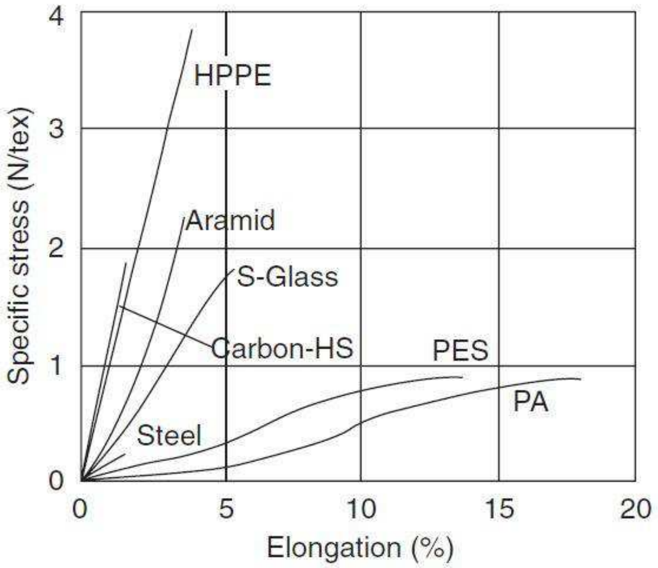

Figure 30. Stress-Strain behaviour of some fibres, HPPE = gel-spun HMPE, PES = Polyester, PA = Polyamide (nylon), HS = high strength. From van Dingenen (2001).

The two equations mentioned in the last page satisfy the requirements of conventional physics and engineering calculations. However, for fibres, area is rarely measured directly but is calculated from linear density (i.e. mass per unit length divided by density). For yarns and ropes, area is an ill-defined concept because of the spaces between fibres. It is therefore better to use the following equation for calculations regarding fibres:

$$Specific\ Stress = \frac{force}{linear\ density} = \frac{stress}{density}$$

If the context is clear from the units or otherwise, the term ‘specific’ is often omitted.

Just like ordinary definitions, modulus and specific modulus characterise the slope of the stress–strain curve. The term can be expanded to initial modulus at the start of the stress–strain curve, tangent modulus at any point on the curve and secant modulus for a line joining the origin to a point on the curve.

5.3.4 Creeping

The time-dependence of tensile properties is defined by *stress relaxation* (stress reduction at constant strain) and *creep* (elongation under constant load) [34].

For polymers, stress relaxation can be a simple description of how they relieve stress under constant strain. Being viscoelastic causes the polymers to behave in a nonlinear, non-'Hookean' fashion and this nonlinearity is later described by both stress relaxation and creep. While stress relaxation means keeping the structure in a strained condition for a finite interval of time (creating some plastic strain), creep is a constant state of stress with an increasing amount of strain [42]. An estimate of stress relaxation is given as the multiplication product of 'creep' and 'modulus', as it is easily measured over short times;

Creep can be measured over a long period of time by hanging fixed weights on yarns and observing the length change at several intervals. Primary creep, which occurs at lower stresses, is recoverable in time under low or zero loads, and the same mechanisms lead to inverse stress relaxation; Secondary creep though, at higher stresses, is not recoverable. Lastly, creep rupture describes failure under a given load.

The molecular mechanisms of creep fall into two categories: The major effect at low stresses as a progressive straightening of molecules, often with a change in the links between molecular segments (usually recoverable and does not affect strength); And at high stresses, where whole molecules slide past one another and this eventually leads to rupture.

The creep of polyester yarns is typically small but augmented by realignment of the rope structure, leading it to require occasional tensioning of fixed lines. Nylon has a greater amount of primary creep and Aramid fibres creep to a smaller extent at low stresses as the pleated structure is extended.

The significance of creep shows itself as a more serious problem in HMPE fibres. When plotted against several decades in the format of log(time), creep follows sigmoidal curves. For most fibres under typical test conditions, creep is in the region of constant or reducing slope. In contrast, HMPE fibres fall in the initial part of the sigmoid. There, although creep starts at a low rate, it then sharply increases after a certain time. Above a certain load and time, HMPE creep becomes constant at a plateau rate, which is shown at the top of the sigmoid. The rate of creep is strongly affected by temperature.

5.3.5 Fatigue

Polymer fibres do not show the crack propagation as opposed to what appears in metal fatigue, but cyclic loading can still lead to other forms of failure. The most common type of such is creep rupture which is often referred to as static fatigue. When the load is cycled from a positive minimum to a peak, the break of nylon and polyester fibres has the same form as in a tensile test and their time-to-break is quite similar as well. However, when cycling from a minimum load of zero (or, for some fibres, a small positive value) to a maximum of half to three-quarters of break load, failure can occur after 10,000 to 1,000,000 cycles, with a different form of break. This break initiates as a small transverse crack, but then turns and runs along and across the fibre so far as the unbroken part fails in tension. One broken end, called the tail, is stripped off the other end. In nylon, Figure 31 (a) and (b), the angle of the crack is about 10° to the fibre axis causing the tail to be about 5 fibre diameters in length. In polyester, Figure 31 (c), the crack runs almost parallel to the fibre axis, and very long tails are found.

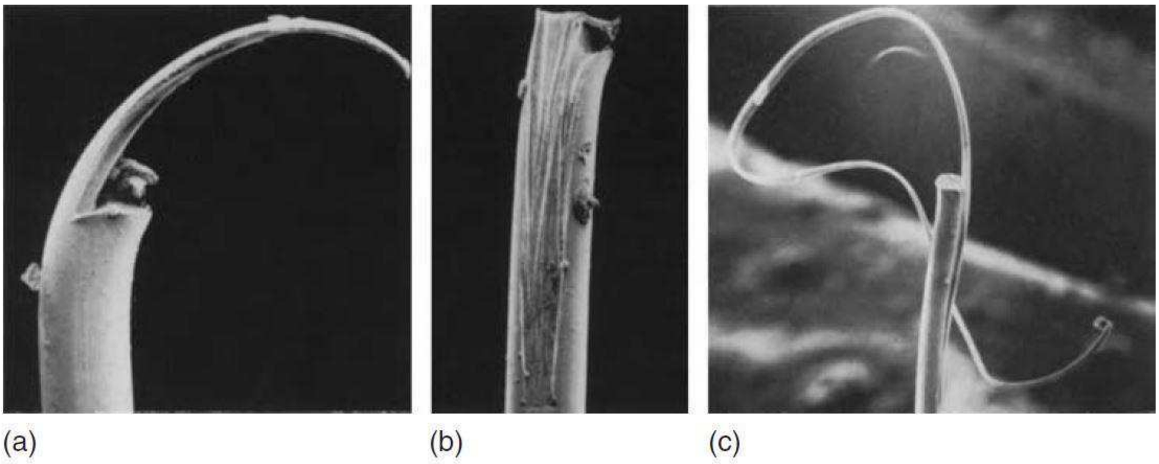

Figure 31. Tensile fatigue failures when cycling from a minimum load of zero; (a) and (b) Opposite ends of break of high-tenacity nylon; (c) Polyester (from Hearle et al. (1998)) [34]

Based on the fact that axial cracks result from shear stress at the tip of the transverse crack, a direct effect of such shear stresses due to inter-fibre abrasion can results in a progressive wearing of fibre surfaces due to shear splitting. This property of rope fibres can be evaluated by the yarn-on-yarn abrasion tester. In this test, two portions of yarn which are twisted together rub against one another under controlled tension due to the cyclic motion executed by rotation of a crank.

An extensive study of yarn-on-yarn abrasion of rope yarns was carried out by Goksoy (1986); Test results showed three different conditions as the severity of the test increased for an increasing number of wraps. Under gentle wear conditions, the rope life was around 1000 cycles; under severe conditions, rope life became less than 100 cycles; between these two regions, there was a sharp transition region with high variability in lengths of lives. The peeling and splitting, which results from inter-fibre abrasion, are illustrated in Figure 32.

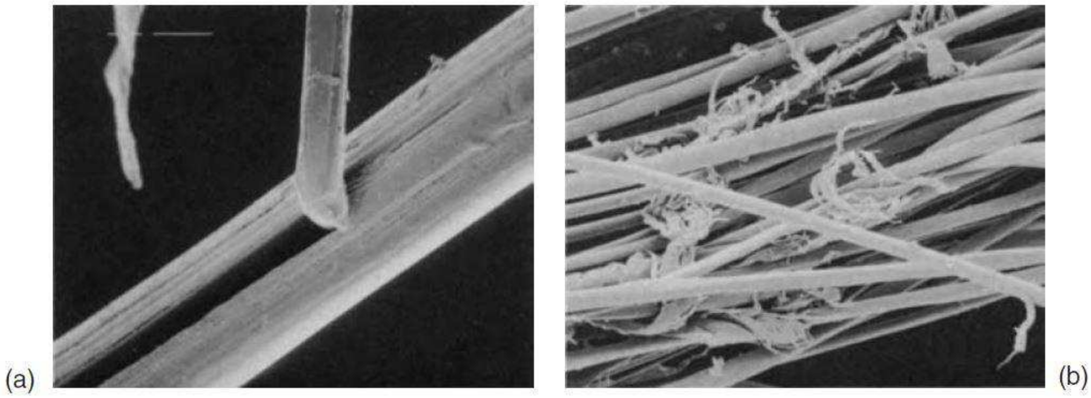

Figure 32. Fibre damage in yarn-on-yarn abrasion testing; (a) Nylon. (b) Polyester (from Hearle et al. (1998)) [34]

5.4 Rope Termination

To properly transmit force a rope needs a termination, whether as a permanent attachment such as a splice, socket or mechanical grip, or a temporary fix such as a knot or wraps around a post. An effective termination is of great importance to almost every application that sets a rope under tension. An eye-splice, Figure 33, is the most widely used and usually the most efficient permanent termination, and should be used wherever possible.

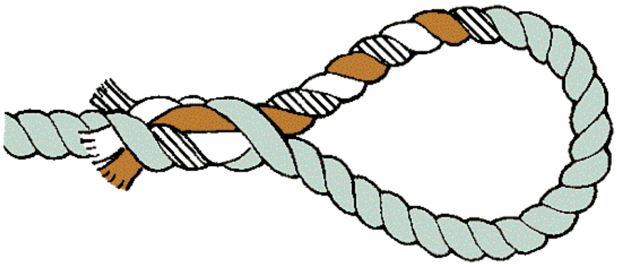

Figure 33. A typical form of Eye Splice termination [43]

A wire or fibre rope is only as strong as its weakest link and this point is often the termination. Local disturbance of the rope structure in the area of the termination can cause a reduction in strength. Also under cyclic tension, abrasion, slippage or kinking may occur at the point of termination and this can lead to a gradual loss of strength and eventually failure.

It is necessary to consider that within the mechanics of terminations, a given stress or percent of break load can cause an increase in the tension when the area of cross-section increases (correlates with second power of diameter) but at the same time, the grip on the rope surface increases as the circumference increases (correlates with first power of diameter). This means that, unless the grip can be spread through internal components of the rope, it is more challenging to make effective terminations on large ropes than on small ropes.

Splicing

The most common and one of the most dependable methods of termination in case of fibre ropes is an eye splice, which allows the rope to be placed around a suitable fitting (as previously shown in Figure 33). The splices are obtained by separating the strands at the ends of the rope from the solid structure, bending the rope into the shape of a loop and tucking the separated strands into the body of the rope. Another approach is to separate the strands, make the shape of an eye, and then braid them over the exterior of the rope; this over-braid will help tighten the grip as tension is applied at the eye. An intermediate stage of tucking the strands in an eight-strand plaited rope is seen in Figure 34. It is evident that there is enough grip on the tucked strands to hold considerable tension, usually up to the maximum breaking strength of the fibre rope.

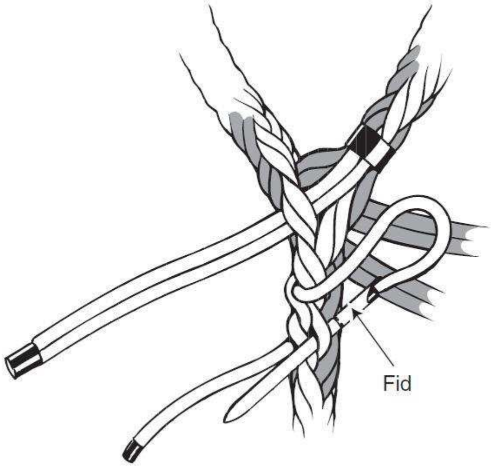

Figure 34. Intermediate tucks in an 8-strand plaited rope eye splice. The fid is a metal tube, used to push strands through rope and under body strands (courtesy of Gleistein) [34]

All fibre rope splice terminations depend on the concept of friction. In general, tucking or burying of strands into the body of the rope is employed as the splicing method. The helical structure of laid and braided ropes will therefore create lateral pressure that enables friction to hold the strands that have been inserted into the main body of the rope. As previously shown in Figure 34, the un-braided strands at the end of the rope are at the beginning of the process of getting tucked into the rope. The lateral pressure (squeeze) created by the strands of the rope body will grip the strands as soon as tension is applied.

Eye splices and grommets (if used) are usually anchored to fittings that have a round surface. Hence, the pressure between the rope and such fittings should be an important consideration. As there is not enough theory present to determine maximum fibre pressure under varying conditions, any possible damage to the rope must be evaluated by test or experience. The damage to the fibre is almost always a consequence of cyclic loading at high interface pressures rather than from the compressive failure of the fibre.

Pressure on the fitting itself should also be under consideration. If polymer-based materials are used as thimbles at the edge of the fitting, the maximum compressive strength of the material may be exceeded. This calls for extra caution to be exercised when testing such fittings; although they may be satisfactory at working loads but can fail catastrophically if used during break testing of the rope. Metal fittings, on the other hand, normally do not have any problem with pressure at their interface.

All fibre ropes flatten to some degree so the area for calculating pressure can only be roughly estimated. To assist these approximations, testing is required to determine the degree of flattening. Once a value for the width after flattening on a pin had been determined, a triangular load distribution from the centre outward would give a conservative value for the maximum pressure at the centre of a pin or thimble (see the equation below). This load distribution can also help in calculating bending stresses in the pin.

$$Max.pressure\ center\ of\ the\ rope = 2 \times tension/(width\ of\ flattened\ rope \times pin\ diameter)$$

5.5 Dyneema® Fibre Designed by DSM

The UHMWPE fibre from DSM Dyneema® is a gel-spun, multi-filament fibre produced from ultra-high molecular weight polyethylene (Figure 35). The main characteristics include high strength, low weight, low elongation at break, resistance to most chemicals, low flammability and non-conductivity. DSM has presented different generations of Dyneema® with the most popular being SK60, SK75 and SK78. A new invention called as 'Dyneema® Max Technology' or DM20 has superior properties than the rest, specifically with a creep factor of almost 0 and hence will be the focus of this study from now on. A comparison can be seen in Figure 36.

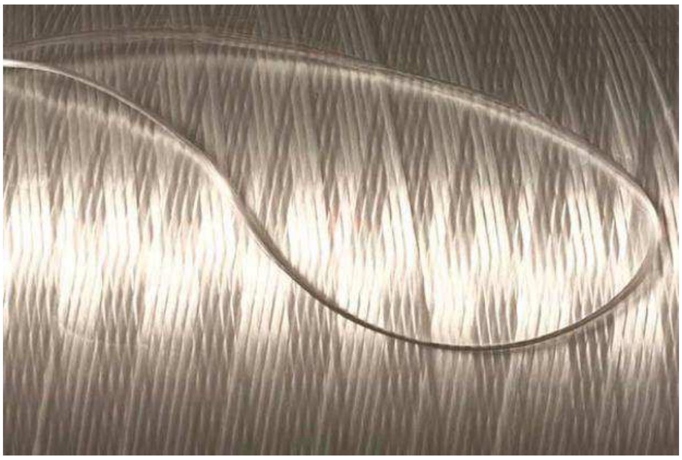

Figure 35. DSM Dyneema® [44]

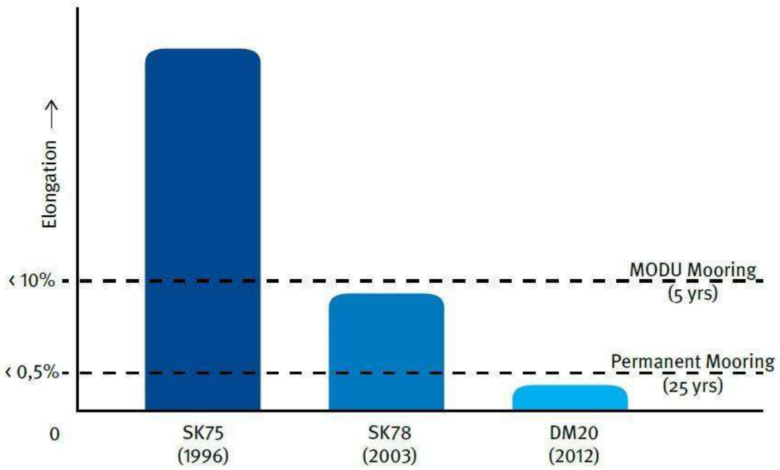

Figure 36. A comparison of elongation in different Dyneema® fibres [45]

5.5.1 Mechanical Properties

UHMWPE fibres have a high strength and a high elasticity modulus in the fibre direction. Considering its low density of 970-980 kg/m^3, this results in an extremely high strength on weight basis. Although the elongation at break is relatively low, but due to its high strength, the energy to break the fibre is high. Moreover, in contrast to many other synthetic fibres, the mechanical properties of Dyneema® are not influenced by the presence of water. As a result of the anisotropic nature of high modulus polyethylene fibres, the modulus and strength in transverse direction are lower than in fibre direction. Subjecting UHMWPE fibre to long-term static loads leads to a permanent elongation called creep. The UHMWPE fibres of Dyneema® have a higher creep resistance than other UHMWPE fibres enabling their use in various static loading conditions [46]. Creep is particularly important in sucker rod pumping operations as an elongated string can in the pump's standing and travelling valve to collide every time the down stroke action comes to end, leading to damage and later leakage within the pump. Hence, properties DM20 would be a significant asset to SR string designs. The mechanical properties of Dyneema® can be seen at a glance in Table 7.

Axial tensile strength	*3.6*	*GPa*
Axial tensile modulus	116	GPa
Transverse tensile strength	0.03	GPa
Transverse tensile modulus	3	GPa
Elongation at break	3-4	%
Rope creep at 30°C, 300 MPa (SK75)	0.02	%/day
Rope creep at 30°C, 300 MPa (SK78)	0.006	%/day
Rope creep at 30°C, 300 MPa (DM20)	0.00007	%/day

Table 7. Mechanical properties of Dyneema® [46]

Like any other synthetic fibres, the mechanical properties of UHMWPE fibres are strongly influenced by temperature. While the strength and modulus increase at sub-ambient temperatures, they decrease at higher temperatures. Hence for long duration exposure, Dyneema® is recommended to be used for conditions up to a temperature of 70°C [46].

Vlasblom et. al. carried out a number of fibre creep rate and creep rupture experiments on SK75, SK78 and DM20 fibres at temperatures ranging from 30°C to 70°C and load levels from 300 MPa to 1700 MPa, comparable to load levels above 20% break load. The results proved that at room temperature, DM20 fiber loaded at 10% fiber break strength shows a creep rate of 0.03% per year; while SK78 showed a creep rate of 2% per year, and SK75 a creep rate of 10% per year. As expected, a temperature increase of 20°C increased the creep rate by approximately a factor of 10.

To better compare the creeping rate, accelerated creep tests were also performed at elevated temperatures to present results in a more appropriate time frame (Figure 37):

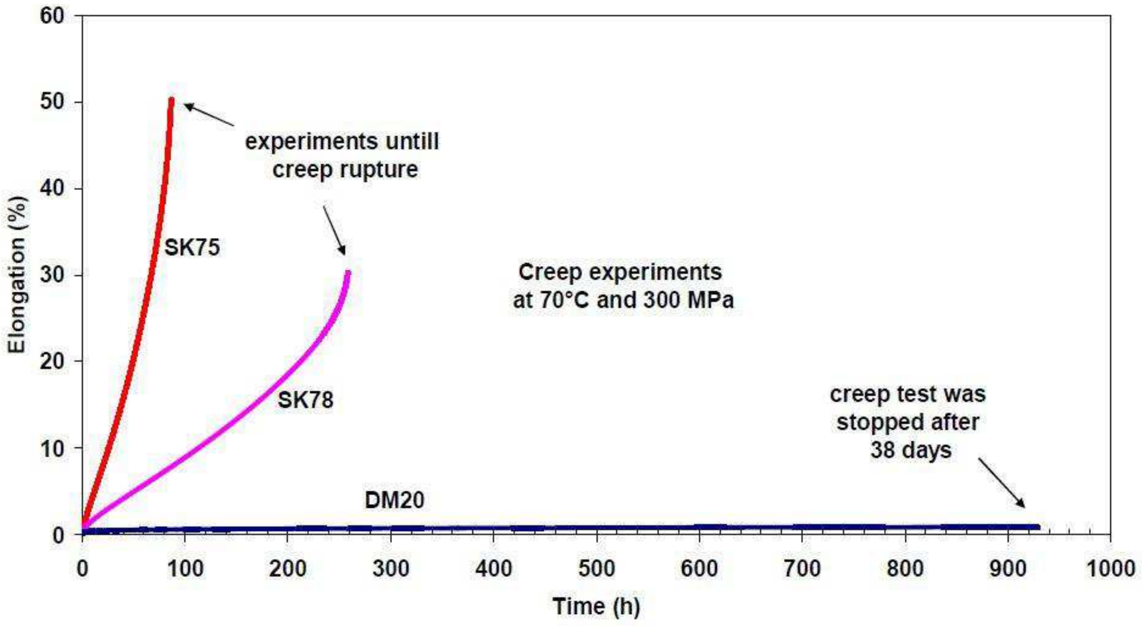

Figure 37. Creep elongation over time for DM20, SK78 and SK75 [47]

Because of time limitations, the experiment on DM20 fibre was terminated after more than 900 hours. Figure 38 also shows logarithmic creep rate over elongation, illustrating the significant reduction in creep rate and low elongations experienced by DM20 [47].

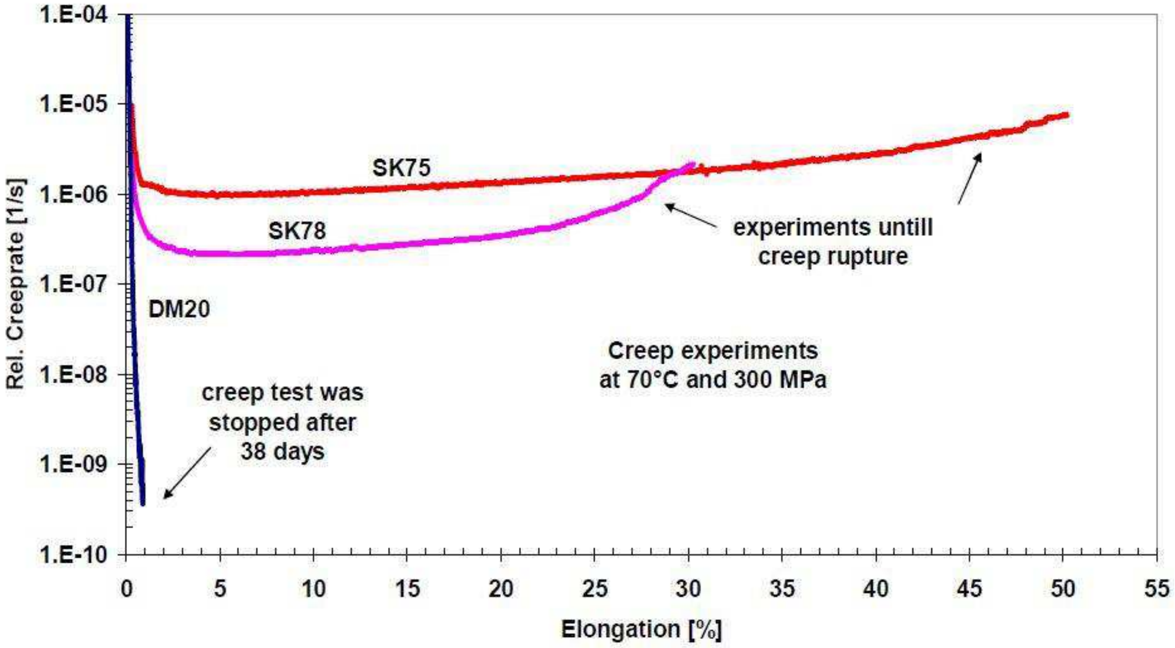

Figure 38. Logarithmic creep rate vs. elongation for DM20, SK78 and SK75 [47]

5.5.2 Physical and Chemical Properties

UHMWPE fibres are generally smooth due to their low friction coefficient. Their low density enables them to float on water. However, the water absorption in the fibre is negligible.

UHMWPE fibre is very resistant against chemicals as it does not contain any aromatic rings or any amide, hydroxylic or other chemical groups that are susceptible to attack by aggressive agents. Dyneema®'s resistance has therefore been regarded as 'excellent' against acids, alkali, hydraulic fluids, lubricating oil and solvents.

5.5.3 Fatigue Resistance

Ropes made of Dyneema® have a higher resistance to repeated axial loading than many other fibre types. The fibres have combined high strength with high fatigue resistance, which proves effective even if the loading is partly in compression as in repeated bending of rope applications. Despite its high modulus, the fibre is flexible and has a long flexural fatigue life. Because of the low friction coefficient and good abrasion resistance, internal abrasion of ropes is usually negligible [46].

5.5.4 Transportation and Installation

Dyneema® fibres are light-weight and therefore very easy to spool and transport. Figure 39 shows a typical transporting truck for synthetic ropes.

Figure 39. A typical synthetic rope spooling setup [48]

5.5.5 Limitations

Although Dyneema® excels at mechanical properties, the maximum endurable temperature still limits the application of these fibres. Company data show that the highest temperature that Dyneema® could be exposed to for long durations is around 70 °C and its melting temperature range is between 144-152 °C. For temperatures above 80°C, the tensile strength and tensile modulus of the fibre will also reduce by 20% and 15% respectively.

Although for the current applications the wellbore temperature does not exceed 60 °C (gradient of 3 °C/ 100m), this factor should also be considered while spooling the fibre in and out of the wellbore. For example, one of the most common applications of Dyneema® is in winch drums where heat can damage the rope during braking. Hence, synthetic-equipped winches have the brake located on the end of the gearbox, to protect the rope [49]. This means that each and every component of the pumping unit must be carefully designed when implementing the Dyneema® rope to avoid any damage to the rope which can lead to loss of the downhole pump.

6 Simulation Methodology

The purpose of this study, as already expressed in the previous chapters, is to select alternative techniques and materials that could replace the current commercial setup of steel rod strings and optimize the operation of the sucker-rod pumping system. This will automatically lead to an increase in efficiency of pumping actions and minimization of the defects that can suspend the process, hence increasing the Mean Time between Failure (MTBF).

The idea of using a continuous rod string has already been explained in Chapter 3 and is the main focus of this project. These technologies are becoming more and more popular since the MTBF shows significant improvement, mainly due to the omission of couplings as a linkage and the highest point of structural weakness. From the four different designs which came up during the literature review procedure, the application of wire ropes was chosen for further investigation and modification. Apart from having all the properties of steel rods, a rope consisting of steel wires is significantly superior to regular rod strings due to their flexibility and easier transportation and deployment. The methodology defined by Hood (1968) has since been developed by a number of companies in different countries.

In this chapter the two recommended continuous ropes, wire rope designed by Voestalpine and Dyneema® fibre rope, will be simulated using a computer modelling software developed in Abaqus to analyse their performance as the sucker rod string in the presence of loads and under cyclic motion. Initially, the idea behind developing the software and its working principles will be described in steps. Further on, the simulation process will be performed for both alternatives and by the end, the results will be analysed.

6.1 Software Description

The sucker rod simulation software was developed in 2015 at the Chair of Petroleum and Geothermal Energy Recovery at Montanuniversität Leoben as part of the Doctoral thesis of Dr. Clemens Langbauer [50]. The software consists of a number of different MATLAB and Python codes which come together to compose the rod string modelling program in Abaqus interface. The idea behind this novel software is to use the Finite Element method to better explain the dynamic behaviour of the string at various points along its length, conceptually requiring two boundary conditions set at polished rod and pump plunger position. The advantage of this software, other than the detailed portrayal of the SR string behaviour, is the elemental analysis of contact between the string and the tubing, an aspect that has never been considered in calculation and simulation methods introduced by API and hence make this program unique in its category. This analysis is of great importance when understanding the effects of friction, reaction force at the polished rod and compression forces which can result in ‘buckling’.

The software also offers the opportunity of designing a tapered rod string, consisting of two or more sections of descending diameters. Moreover, it is also possible to include rod protectors in the structure at certain positions within the string to analyse the contact forces in realistic scenarios (more details in Step 4).

In order to create the model, multiple input files should be generated. Different stages of this process are explained below:

Step 1: Definition of mesh

Definition of string components, also regarded as 'numerical mesh', is done with elements and nodes. A conventional sucker rod string consists of 25 to 30 feet steel rods, commonly having 2 to 4 rod protectors on each piece. In this modelling approach, regardless of this segmental design and as a rule, nodes are set on the position of protectors and precisely between them. Even if no protectors have been used, the designation follows the same rule.

In order to collect nodes into elements, Abaqus offers a B32 beam element analysis in which each element consists of 3 nodes and 2 integration points at which stresses are observed. This arrangement is shown in Figure 40:

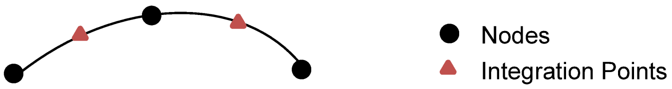

Figure 40. Definition of a B32 element

To prepare this data, a MATLAB file is written specifically to generate a number of text files, not only defining the nodes and elements for the proposed string, but also describing the following parameters for the corresponding nodes/elements:

- Cartesian coordinates of the nodes
- Measured depth at each node
- Direction of the tangent at each node
- Nodes and elements within a taper
- Equivalent nodes defined on the tubing string
- Spring elements at each node (explained later in Step 3)
- Fluid friction at each node

It is important to note that since for each taper nodes can be in the position of rod protectors or in between, two different set of nodes (two different text files) in odd and even numbering format will be generated for each taper, e.g.:

- Taper 1 – nodes on protectors
- Taper 1 – nodes not on protectors
- Taper 2 – nodes on protectors
- Taper 2 – nodes not on protectors

This characterisation is particularly important for the description and later presentation of contact forces between rod string and tubing.

Step 2: Definition of Load and Movement

As explained before, a partial differential equation requires at least two boundary conditions. In this model, these conditions are expressed in terms of 1) the vertical motion of the polished rod at the top end of the string and 2) the immobility of the tubing as it is considered to be anchored at the bottom.

The former, requires a description of the load and movement vs. time at the polished rod. As the movement of the polished rod in the stuffing box is strictly vertical, it has to be specified with the term ‘ZASYMM’ in the Abaqus code. Later, the two mentioned datasets are created by a secondary MATLAB code in the format of text files. Some case-dependant data such as SPM, SR string diameter, pump size and some fluid and well data must be inserted into the code to generate these files (explained in details in section 6.2). An additional file including calculated data for fluid friction on the string (using CFD simulations) is further added to these two datasets, all of which contribute to the input file required by the Abaqus program.

As for the stationary tubing string, the status is defined in the code with the term ‘ENCASTRE’, therefore limiting all nodes on the tubing to their initial position at all times.

Step 3: Definition of installation mode

In a standard installation, a sucker rod string is attached from the top end to the polished rod and from the bottom end to the pump plunger and is free to move along the tubing string. During the lift process, the inside of the tubing and pump barrel is filled with the reservoir fluid that in an ideal case surrounds the SR string and pump plunger completely. In case of an immobile string, this fluid creates a buoyancy force, tending to push the plunger upwards. However, at the same time, it also creates a radial force that will readjust the string to the centre of the well in case the buoyancy force is large enough to cause buckling. This radial effect can be expressed in terms of a ‘spring action’ caused by the fluid. In an active system, the reciprocating string faces greater compression forces that render the spring effect almost inadequate. This phenomenon is more problematic in high-speed operations and can cause serious damage to the string as a result of constant friction with the tubing.

This impracticality is the basic foundation of the innovative system[1] called ‘SRABS’ (Sucker Rod Anti-Buckling System) which cleverly minimises the buckling effect by a simple readjustment of the downhole components. In this design, the length of the rod string is extended to let it pass through the pump barrel and exit at the bottom, creating a situation where the liquid column in the tubing no longer has a buoyancy effect on the bottom of the string. Instead, the only buoyancy effect is applied by the liquid column in the annulus and

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[1] Patent Nr. PCT/EP2008/004373, Montanuniversitaet Leoben, June 2008

since the dynamic liquid level in the annulus is way lower than the height of the liquid column in the tubing, the buoyancy forces will be significantly decreased.

This installation can further be improved by adding a tensioning element below the pump. In principle, the pumps used for this model are pull-down pumps. Therefore, the addition of a heavy weight below the pump not only facilitates the pump operation but also helps maintaining the entire string in tension.

Figure 41 depicts the pumping mechanism of a SRABS installation in a simple manner.

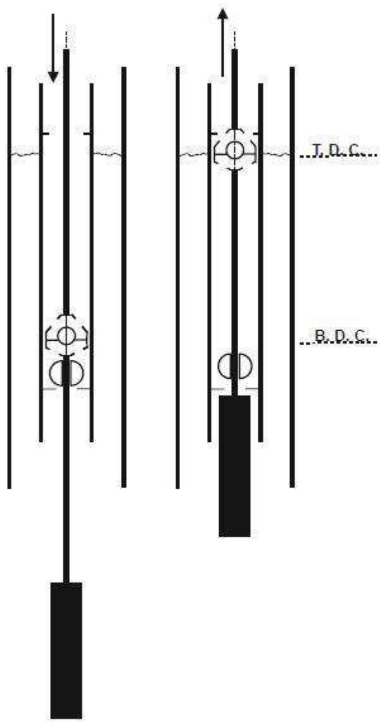


Figure 41. Performance of a SRABS pump with a weight [51]

During the simulation process, it is possible to choose either a standard system or a SRABS installation by changing the load calculation during downstroke in the related MATLAB file. The addition of a weight below the pump can also be implemented however the node and element designations have to be slightly changed to accommodate this extra section within the string.

The detailed illustration of a SRABS pump can be seen in Appendix A – SRABS Setup Illustration.

<u>Step 4: Main Abaqus code</u>

Once all the elements' and boundary condition input files are ready, the main Abaqus code should be put into operation to recall text files one by one. Depending on the test specifications, other physical properties of the used material such as Poisson ratio, modulus of elasticity and diameter of the string should also be inserted. The prepared code allows for introduction of two tapers or more, which for the design of a continuous string means similar characteristics for all tapers.

In addition, the spring effect is also applied by introducing a text file that contains values for spring constant at each node of the string. As explained before, 4 different text files are generated for a 2-taper string with nodes on/off the rod guides. For each case, a friction factor between string/tubing and protector/tubing as well as the clearance (radial distance between string/tubing and protector/tubing) will be placed in the code. Accuracy calls for introduction of a ‘non-structural mass’ to account for the weight of auxiliary parts like protectors, cover or wax between the wires. This value can be reduced or omitted depending on the setup.

Furthermore, the behaviour of the string depending on its consisting material must be clearly defined. In this study, an elastic behaviour for both wire rope and fibre rope has been assumed. Together with the value for material density, the dampening of the string is modelled more precisely. Lastly, the boundary condition files are brought in with the additional two terms that describes their status.

One of the most important parameters to include within the calculations is the speed of pumping expressed in ‘strokes per minute’ or SPM. A pump can operate in rates of approximately 2-25 SPM depending on the producing reservoir and system capabilities. This simulation is programmed for 3 seconds of initial static state, followed by 2 complete pump cycles. Hence, it is important to specify the pumping SPM in order to get a full operational period. Furthermore, due to the geometry of the SRABS pump and the fact that the rod inside the pump reduces the barrel volume, the values of SPM for a SRABS setup would be slightly higher than its equivalent standard pump for similar production rates.

Once the model is created in Abaqus, it is possible to observe the motion of the string in full scale. It is also possible to analyse the contact forces, stresses, movement etc. on any node or within an element.

Step 5: Information Cube

Abaqus creates a number of output files with different extensions. At this point, a special program written in Python will gather the information from these files and starts with generating an information folder. The goal is to gather contact force, stress and displacement data from all nodes at various points in time. Once the program has finished its run, several folders are created, each for a specific timestamp, containing 3 data files for the 3 parameters mentioned before. Next, a new MATLAB code will come into play and creates an information cube consisting of these 3 parameters.

It is important to note that the python code also provides 3 extra files for any simulation, explaining the time increments, reaction force at polished rod and displacement at the plunger. These files will come together in the final MATLAB code that will be performed to derive data from the information cube and create a pump card as well as calculate values for energy, power consumption, etc. for the entire system or plot these parameters and their change with respect to time.

One of the most important outputs of this code would be the stress distribution along the length of the string which can clearly indicate the areas suffering from high tension or compression and the changes when implementing different materials or techniques.

A flowchart of the simulation process can be seen in Appendix B - Simulation Workflow.

6.2 Proposed Setup

So far, the theory of continuous SR's, the suggested techniques and materials, and the method of analysis have been described. In this chapter, the specifications of the recommended setup will be explained in details for simulations:

6.2.1 Selected Wells

In order to gain a better understanding of the SR string behaviour in different operation scenarios, two different wellbore geometries have been chosen and the corresponding text files were generated to define the number and position of nodes and elements. The basic fluid characteristics, wellbore information and pumping system specifications can be seen in the Table 8:

Specifications	Vertical Well	Slanted Well	Unit
MD	739	893	m
TVD	739	877	m
Inclination	-	28	°
Temperature	61	33.3	°C
R_s	0.45	0.23	-
WC	98	86.6	%
Fluid density	905	920	Kg/m^3
Tubing ID	2.995	2.441	in.
Tubing head pressure	5	2	bar
Casing head pressure	4	4	bar
Dynamic fluid level	456	879	m
Pump specifications	C-640D-305-168	C-320D-256-144	-
Pump type	Tubing pump	Insert pump	-
Surface stroke length	168	144	in.
Plunger diameter	3.75	1.5	in.
Plunger length	4	4	ft.

Table 8. Fluid, wellbore and pumping specifications of the wells

6.2.2 Selected Material

The simulations will be performed with three different materials in the following arrangements:

1) Conventional sucker rod (CSR) with two tapers of 7/8" and 5/8" diameter and 1.5" sinker bars
2) Pre-stressed wire rope (courtesy of Voestalpine AG) with 15.7 mm diameter
3) Fibre rope made of Dyneema® DM20 (courtesy of DSM) with 15 mm diameter

Table 9 describes the basic properties of CSR, wire rope and fibre rope:

Material	**Composition**	**Diameter**	**Density**	**Weight per Length**	**Elongation at Break**	**Break Load**	**Modulus of Elasticity**	**Tensile Strength**	**Poisson Ratio**	**Temperature Limit**
(Unit)	-	mm	g/cm3	kg/100m	%	kN	GPa	GPa	-	°C
Conventional SR	Steel	15.9	7.85	250	4.17	221.3	192	0.8	0.3	-
Wire Rope (Voestalpine)	Steel	13.6	7.81	117.2	0.99	251.7	187	1.8	0.3	-
Dyneema® (DM20)	UHMWPE	15	0.975	13.4	3.6	237	90	3	0.29	70

Table 9. CSR, Wire rope and Fibre rope data

In the table above, the diameter of wire rope has been indicated as 13.6 mm instead of 15.7 mm. The reason for this difference is that a wire rope does not have a fully circular cross-section which means that the bending stiffness of the rope will be slightly less than that of a solid rod with the same diameter. Therefore, to obtain the equivalent rod diameter that has the same characteristics of a 15.7 mm wire rope, the equation for momentum of inertia will be used as below:

$$I_{rod} = \frac{\pi {d_{rod}}^4}{64}$$

$$I_{wire\ rope} = 3 \times \frac{\pi {d_{wire}}^4}{64} + 4 \times \left[\frac{\pi {d_{wire}}^4}{64} + \frac{\pi {d_{wire}}^2}{4} \times l^2 \right]$$

where 'd' is the element diameter, and 'l' is the bending diameter. By equalizing the equations, the diameter of a rod with similar bending stiffness of the 15.7 mm wire rope would be 13.6 mm.

6.2.3 Other specifications

All three materials will be simulated for both the vertical and the slanted well. While the conventional SR is used with a standard pump, wire rope and fibre rope have been designed to work with the SRABS pump, with fibre rope also using a tensioning element below the pump. Two different pumping speeds in terms of SPM will be set for each material at each well: a low SPM of 5 (5.95 in SRABS) and a high SPM of 10 (11.98 in SRABS). It is also considered that the tapered CSR and the wire rope use protectors for friction protection and centralization purposes; while the fibre rope does not take protectors due to its low friction factor with steel and, more importantly, to assist its spooling action. The string arrangement of the three models can be seen in Table 10:

CSR	Vertical Well	452 m (7/8” rod), 267 m (5/8” rod), 26 m (1.5” sinker bars)
	Slanted Well	800 m (7/8” rod), 61 m (5/8” rod), 30 m (1.5” sinker bars)
Wire rope	Vertical Well	745 m (13.6 mm wire rope)
	Slanted Well	891 m (13.6 mm wire rope)
Fibre rope	Vertical Well	745 m (15 mm fibre rope), 15.2 m (1.5” tensioning element)
	Slanted Well	891 m (15 mm fibre rope), 15.2 m (1.5” tensioning element)

Table 10. SR string orientation for the three considered materials

A simple description chart of the simulation cases and the wellbore geometries can be found in Appendix C – Simulation Cases.

6.3 Design Options

Aside from the installation setup, miscellaneous components and enhanced production scenarios will also be considered in this study. Some of these possibilities are discussed in the following sections:

6.3.1 SRABS versus Standard Pump

The effects of a SRABS system can be seen in the stress distribution profile of the string. Figure 42, which belongs to one of the simulation cases with a CSR, shows the stress distribution along the string during up and down stroke. It is visible that when using standard pumping units, the string will buckle right above the sinker bars during the downstroke. This is visible in the profile as simultaneous levels of tension and compression, an indicator of buckling. However, if a SRABS pump is used, the buckling effect is removed.

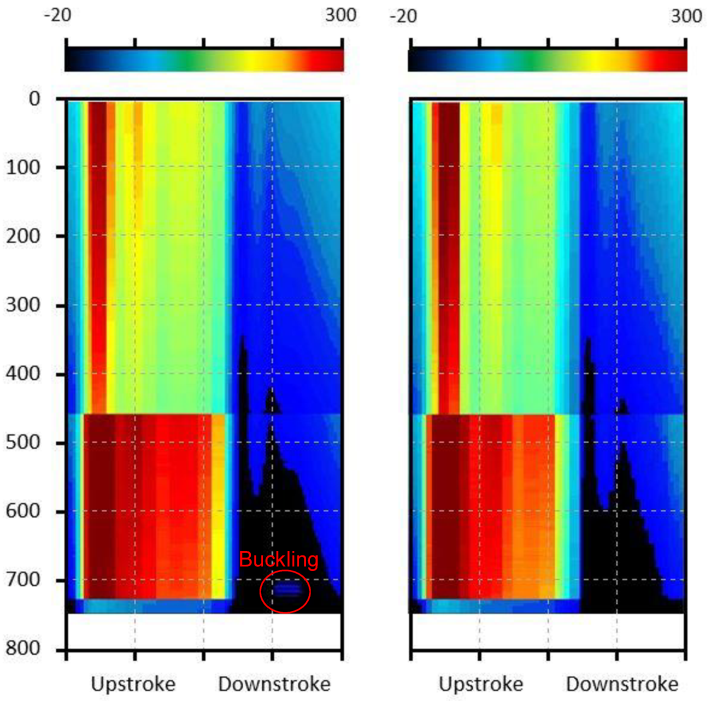


Figure 42. The difference between a standard (left) and a SRABS (right) pumping system in terms of buckling occurrence in the vertical well

6.3.2 Operating in an in-lined Tubing

Internal plastic coatings have been used for corrosion protection, hydraulic improvement, and deposition mitigation in tubings and drill pipes for over 60 years. They have proven to be a long-term corrosion control solution, even with difficult to treat applications such as top of the line corrosion. As for hydraulic efficiency, internal plastic coatings have shown to be able to improve overall flow and a means to reduction in pipe size simply by reducing the surface roughness and inherent surface friction. In case of deposit mitigation, internal plastic coatings own the ability to reduce or completely stop the adherence of deposits onto the pipe surface. These benefits have been proven effective in applications from subsea pipelines to simple flowlines tying into an onshore wellhead [52].

One of the aims of using wire ropes instead of the current tapered rod strings is to reduce the number of auxiliary equipment used in the borehole, i.e. couplings, pony rods, rod protectors etc. If the tubing is in-lined with a special polymer, the wire rope can be implemented without protectors or covers as the contact force would occur with tubing and rope roles reversed and a friction factor that stays almost intact.

6.3.3 Implementation of Rod Protectors

Rod protectors or rod guides are commonly used with conventional sucker rods to eliminate the contact force between the tubing and the rods. They are made of various grades of plastic (e.g. nylon) and they include a percentage of Teflon in the chemical composition.

Protectors also help cleaning the tubing with their special shape that helps remove wax and paraffin from the walls.

But one of the key advantages of using protectors is to allow the SR string to stay in parallel with the tubing and to limit the string's mobility in planar directions. This is primarily the reason why protectors have been considered in the wire rope setup as well since simulations with no protectors could not be completed. To install a wire rope without protectors, the SRABS pump must be used in combination with large tensioning elements below the pump and to avoid high friction forces, the they should only be installed in wells only with an in-lined tubing.

6.4 Design Challenges

Since the simulation codes have been written to model and analyse the performance of sucker rods, the replacement of geometry to that of a wire or fibre rope can raise multiple challenges. This is mostly due to the complex behaviour of the ropes as well as the flowing fluid and also the limitations in introducing alternative pumping units that can assist the operation of a system using wire and fibre ropes. Two of the most dominant and frequent issues are described below:

6.4.1 Geometry of Fibre Rope

Dyneema® fibre's DM20 has a density of 0.975 g/cm^3 which makes it one of the lightest synthetic fibres available in the market. Although this quality is quite accommodating in handling and transportation of this fibre rope, it can be problematic when implemented as the SR string into the well. As explained before, the SRABS pumps are pull-down pumps and are activated with tension force rather than compression. Although this facilitates the movement of the fibre rope, it can still be insufficient as the fibre may become incapable of extending in time during downstroke when pumping with high SPMs. This means that the fibre rope can also start floating when the load of the dynamic liquid column in the annulus is substantial, i.e. in the vertical well. This is the main reason that the simulation of fibre rope in the vertical well with maximum SPM was interrupted half-way as the system could not process the movement of the rope in such conditions.

6.4.2 String Stretch

Since the pump plunger is located hundreds of meters below the polished rod, the SR string tends to stretch due to its self-weight even before the pumping action begins. This stretch is also one of the reasons why the stroke length at the plunger is never equal to that of the polished rod.

String stretch also occurs as a result of liquid loads on the plunger and their dynamic effects. In better words, the higher the liquid load, the higher force required to move it upwards (inertia effect). A sudden and significant stretching at the beginning of the upstroke can cause a lag between the polished rod stroke and the pump stroke which leads to under travel in most cases. Figure 43 depicts the effect of stretching in a CSR in the vertical well with low

SPM. The red curve shows the movement of the polished rod in z-direction in time while the blue line represents the movement of the plunger. As can be seen, the string is already in stretch before the pumping begins (3 seconds of static conditions) and once the polished rod starts the upstroke, the plunger is further stretched before it follows the reciprocating movement. This also results in delay in initiating downstroke, as can be seen in the difference of the curves' peaks.

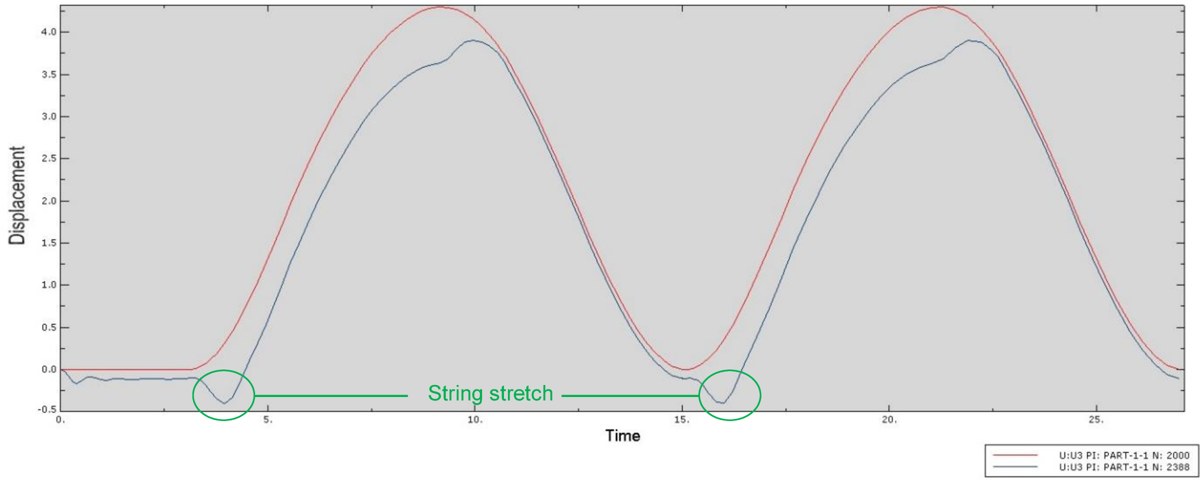


Figure 43. String stretch in the CSR, in vertical well and with low SPM

Generally, this phenomenon is most common to occur when using conventional sucker rods made of fibreglass. Fibreglass has a smaller elastic modulus than steel and is therefore more susceptible to stretching. In cases like this, it is advised to increase the diameter of the string to lessen the strain. This is practically the most important reason why smaller-diameter wires or fibres are not used, although their tensile properties are sufficient to handle the load scenarios.

There are 4 criteria in this project's simulation cases, all of which can contribute to stretching:

1) Compressibility of the produced liquid
2) Plunger size (group 2 well)
3) Type of well (vertical or non-vertical)
4) String material's elasticity

The produced fluid consists of 90% water which is an incompressible fluid with high inertia. In addition, the vertical well considered for this project uses a tubing pump with a plunger diameter of 3.75 in. and belongs to the group 2 wells (wells less than 4000 ft deep and plunger diameter higher than 2in.). Compared to the pump plunger of the slanted well with 1.5 in. diameter, it is evident that this can lead to a larger liquid load. Moreover, the vertical well allows the liquid to imply its full gravitational weight on the plunger as opposed to a slanted well where a portion of the liquid weight is supported by the tubing. These factors have created a problematic situation in the vertical well, more specifically for the fibre rope, with the lowest elastic modulus as it possesses all of the stretching criteria, resulting in a very small effective stroke length in these scenarios. Figure 44 shows the stretching effect in this case:

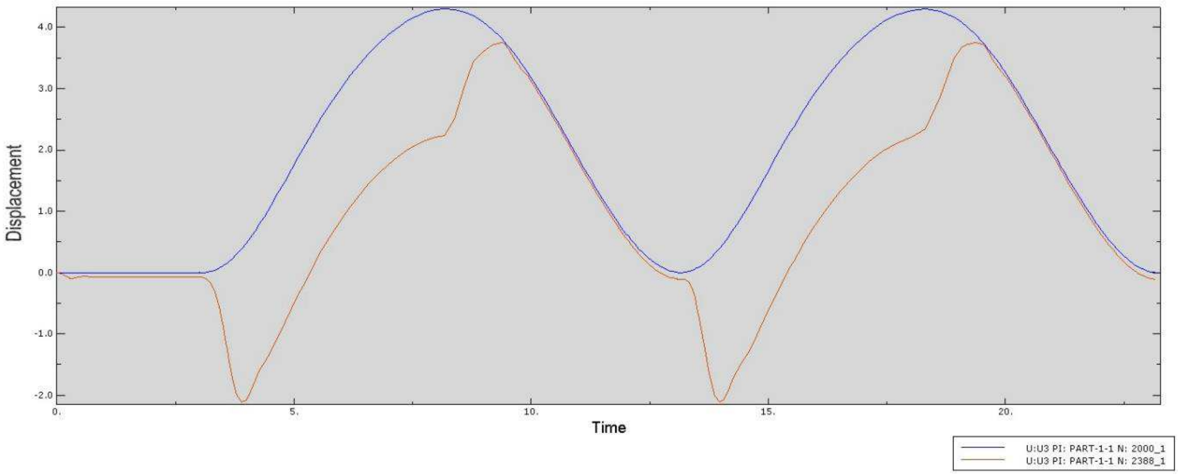


Figure 44. String stretch of Fibre Rope, in vertical well and with low SPM

This problem can be resolved by using long-stroke pumping units with stroke lengths as long as 10m. Since most of the common long-stroke units work with hydraulic fluid in which leakage and environment contamination is a regular deficiency, new surface units should be designed to facilitate this system with proper components. The geometry of the fibre ropes is very well suited to accommodate itself in these setups. However, the current software needs to be re-programmed to be able to account for this change. Table 11 shows different effective stroke lengths and their effect on production rate for all simulation cases. The outcome of stretching can be visibly seen in the numbers:

	SPM	**Slanted Well**		**Vertical Well**	
		Effective plunger stroke length (m)	Production rate (m^3/day)	Effective plunger stroke length (m)	Production rate (m^3/day)
Polished rod	-	**3.66**	-	**4.27**	-
CSR	5	3.05	22.53	3.75	27.70
Wire rope	5.95	2.92	21.21	3.03	22.01
Fibre rope	5.95	2.85	20.71	2.2	15.98
CSR	10	3.12	46.10	3.86	57.03
Wire rope	11.98	2.92	42.71	3.17	46.37
Fibre rope	11.98	2.75	40.23	-	-

Table 11. Effective stroke length and production rates for different simulation cases

7 Results

The performance of different materials as the SR string can be evaluated with three different parameters: stress distribution, stroke efficiency and energy consumption. The following sections discuss the results of the simulated cases with the help of these parameters:

7.1 Load and Displacement vs. Time

The best visual representation of the load and displacement in a pumping system is through the polished rod and pump cards. Studying these cards is the simplest yet most precise way of understanding the surface and downhole conditions. However, due to the restrictions of the software, the generated pump cards had a slightly different shape than normal. Consequently, graphs of Load vs. Time and Displacement vs. Time were chosen to be presented in this study for more accuracy. Figure 45 shows these profiles for one of the simulation cases. The rest of the graphs for all other cases can be viewed in Appendix D – Load and Displacement Profile at Pump.

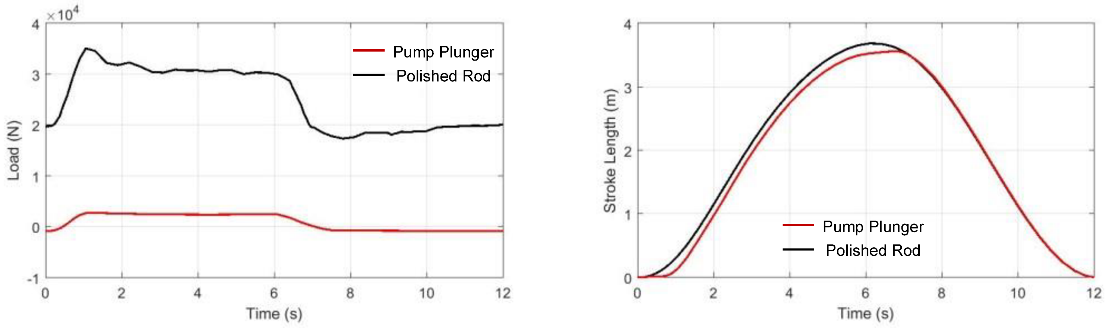


Figure 45. CSR in slanted well, low SPM

As expected, the effect of stretch at the beginning of upstroke can be seen in the displacement profile of wire and fibre ropes, with the corresponding inertia effect evident in the load profile. These indicators, are more severe in pumping conditions within the vertical well. This leads to a reduction in effective stroke length and as a result, a decrease in fluid deliverability to the surface.

Obviously and owing to the presence of the dynamic fluid load, the polished rod load profile is more distorted than the pump's, with the unsteady pattern increasing as SPM peaks. On the contrary, the displacement behaviour of the polished rod is smoother than the pump's, this time because the dynamic fluid load affects the underlying pump's motion.

Another considerable dissimilarity is the reduction of the area between the polished rod and pump load profile, an indicator of the loads handled by the polished rod, as the system is switched from CSR towards wire and then fibre ropes. This phenomenon is caused by the smaller self-weight of the string and can vastly reduce the system's picked up load and thus its energy consumption.

7.2 Stress Distribution Comparison

Examining the stress distribution of a sucker rod string can provide visual information on areas with the highest tension and compression forces. A profile for the CSR, wire and fibre ropes in the slanted well operating at low SPM can be seen in Figure 46. Other profiles for all cases can be found in Appendix E – Stress Distribution Graphs.

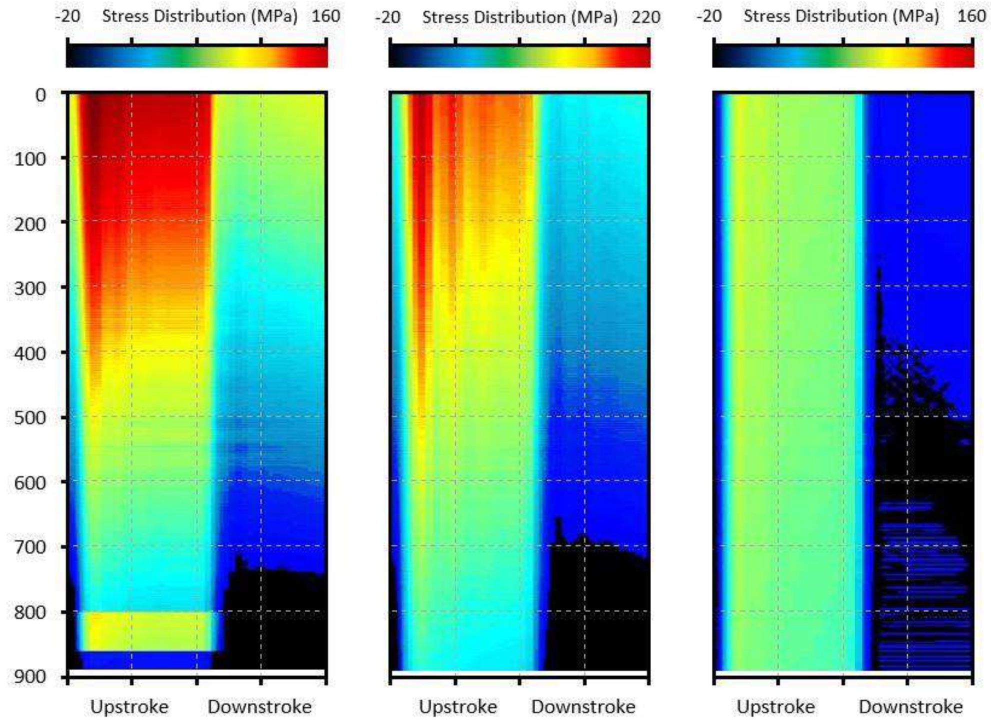


Figure 46. Stress distribution in the slanted Well, low SPM, from left to right: CSR, Wire Rope, Fibre Rope

Looking at the stress distribution during the upstroke, since the CSR is deployed with two tapers of 7/8" and 5/8", the peak stress at the top of the string is less than the case of wire rope as it has a larger diameter at the uppermost section which helps distributing the tension (relationship between elasticity and stress). As expected, these stresses increase in the extreme case of the vertical well due to larger dynamic liquid loads.

Yet, even in the most extreme scenarios of a wire rope setup, the tension is still less than one third of the wire rope's tensile strength, making it an asset for operations where large stresses are involved. In the case of fibre ropes, the exceptionally light weight of the string leads to way lower tensional forces, even less than 0.2 of its tensile strength at the most extreme pumping scenario, and an almost steady distribution of stress along the length of the rope. It means that if a fibre rope is used instead of the SR string, points or sections of high stress with high failure probability will no longer exist as the fibre can spread the load equally along is length and hence minimize the chance of breaking.

In the course of the downstroke, the CSR and the wire rope experience buoyancy forces but only in the case of the vertical well and at high SPM's do they experience buckling. This matter can be resolved in the application of wire rope by installing weights below the pump to mitigate the string damage. It is also possible to refrain from high-speed pumping and settle for the low 5.95 SPM velocity.

Where fibre rope is used, buckling is inevitable as protectors were not implemented on the rope either. Still, the small friction factor between the fibre and the tubing will not lead to damage or deficiencies and therefore the setup will be left untouched.

7.3 Energy Consumption Comparison

The applicability of any system eventually comes down to its productivity with respect to the input energy. For a sucker rod pumping unit, optimization of performance is theoretically done by adjusting the surface counterweights so to either minimize the input energy itself, or minimize the total torque.The simulation software, runs a code in which the total torque is calculated for a range of different counterweights. As the curves are plotted verses the rotation angle, the program specifies at which counterweight the peak torque of the system is the smallest. The resulting curve would represent the minimum torque scenario. Similarly, for the input energy, the program runs the same code to determine at which counterweight the system requires the smallest input energy. These two optimization categories are expressed as 'Scenario T_{min}' for minimum torque and 'Scenario E_{min}' for minimum energy.

Previous research at the Chair of Petroleum and Geothermal Energy Recovery shows that for any amount of energy given to a pumping system during the upstroke, there will be some generated or recovered energy during the downstroke which, if procured right, can be used as feed to the same unit or one located nearby. This is mathematically shown as the area of the torque vs. angle curve bellow the x-axis. In an ideally balanced unit, the amount of the consumed and generated energy is equal, yet as units are often not properly balanced in reality, the input energy is larger than the generated one. Regardless of the amount, it is still good practice to calculate the minimum generated energy (E'_{min}) for all systems to gain a better understanding of the effectiveness of pumping action.

Figure 47 presents two different graphs analysing the two different scenarios:

- The graph on the left, shows the power consumption of the system for Scenario T_{min}, input energy for Scenario E_{min} and the system's minimum generated energy (E'_{min}) as a function of counter torque.
- The graph on the right, shows total torque for all counterweights (spectrum in green) and the curves for Scenarios T_{min} and E_{min}.

Further graphs can be found in Appendix F – Torque and Energy Graphs for all cases.

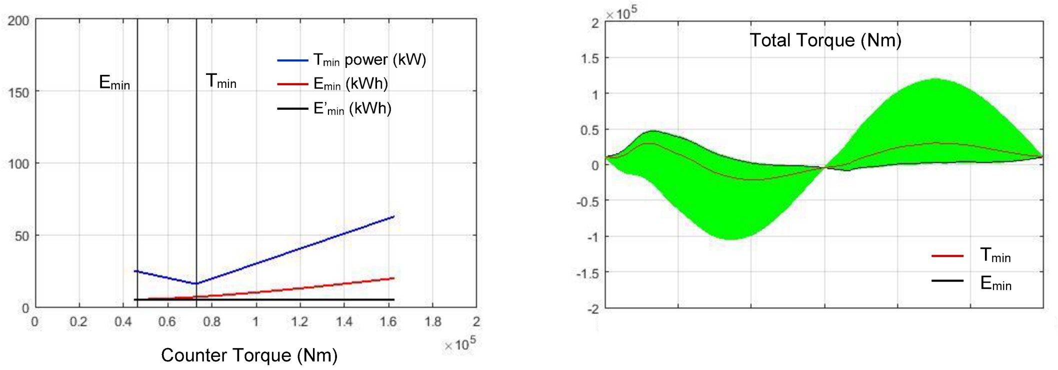


Figure 47. Torque and energy scenarios (CSR, slanted well, low SPM)

Table 12 presents the counterweights, power and energy consumption for the minimum torque and energy scenarios as well as the minimum generated energy for all simulation cases. Furthermore, the energy efficiency of all systems, expressed as the amount work the pumping unit does to deliver wellbore fluids to the surface in exchange for the energy it receives from the prime mover, is also calculated.

The numbers indicate that in the T_{min} scenario, energy and power consumption of the wire rope, except in the case of the slanted well with low SPM, is higher than the CSR. Whereas the fibre rope consumes the least energy and power in the slanted well while the values lie between wire rope and CSR in the vertical well. In contrast, for the E_{min} scenario, the energy and power values reduce in the slanted well as the system is swtiched into wire rope and later to fibre rope. Still ,the CSR is a better option for the vertical well installation.

Looking at the effiency calculation results, the fibre rope system in the slanted well owns a higher value in all three scenarios compared to the wire rope. This growth is also visible when compared with the CSR in minimum torque and minimum energy generation scenarios. This improvement is noteworthy since the effective stroke length in fibre ropes is least of all three systems, yet because of the lower friction losses (small friction factor between the fibre and steel tubing), the torque and energy requirements are reduced enough to compensate for this loss.

Conversely in the vertical well, due to the excessive dynamic liquid load and the limitations of the installed pump, the efficiency of all systems drop down considerably. This reduction is more severe in the case of fibre ropes, as previously explained in section 6.4.2. But a wire rope setup still has a better performance and therefore if extreme pumping conditions exist, of the two new string types, wire ropes should be the choice.

	SPM	Scenario T_{min}			Scenario E_{min}			E'_{min}	Efficiency Scenario T_{min}	Efficiency Scenario E_{min}
	-	P_{max}	E	$T_{counter}$	P	E_{min}	$T_{counter}$	$E_{min,gen}$		
	-	(kW)	(kWh)	(kNm)	(kW)	(kWh)	(kNm)	(kWh)	(%)	(%)
Slanted_Standard_CSR	5	16	6.9	73.2	24.6	5.2	46.2	4.7	29.5	39.1
Slanted_SRABS_Wire	5.95	15.7	6.6	40.6	19.4	5.6	30	4.2	29	34.2
Slanted_SRABS_Fibre	5.95	12.7	5.3	15.6	15.8	4.9	7.3	3.6	35.3	38.1
Slanted_Standard_CSR	10	49.3	20.2	87.4	76.6	13.4	47.3	9.7	20.6	31
Slanted_SRABS_Wire	11.98	50.2	20.4	50	67.2	16.1	30	8.1	18.9	23.9
Slanted_SRABS_Fibre	11.98	40.2	16.1	24	53.4	13.8	6.4	6.6	22.5	26.3
Vertical_Standard_CSR	5	33.9	15	99.1	38.8	14.4	83.8	14.3	14.3	14.9
Vertical_SRABS_Wire	5.95	41.4	17.4	81.8	48.5	16.6	63	16.2	9.8	10.2
Vertical_SRABS_Fibre	5.95	36.1	16.6	5.7	38.8	16.5	50	16	7.4	7.5
Vertical_Standard_CSR	10	107.1	40.8	129.8	152.7	33	66.2	31.1	10.8	13.4
Vertical_SRABS_Wire	11.98	147.7	53.5	120.4	219	40.3	41.5	36.5	6.7	8.9
Vertical_SRABS_Fibre	11.98									

Table 12. Results of the torque and energy analysis

8 Conclusion

The capabilities of a new high-strength wire rope manufactured by Voestalpine AG and a Dyneema® fibre rope were analyzed and simulated in the course of this project to introduce new materials that have ultra-high tensile strength and minimum creep; The aim of these innovations is to extend the MTBF and provide means of easier transportation and faster deployment.

Comparing the results of 12 simulations on implementing these two ropes with a conventional sucker rod verifies that the performance of the recommended systems is strongly dependent on wellbore geometry and pump specifications.

The fibre rope, simulated with no protectors, could activate a state-of-the-art SRABS pump despite its light build and low elastic modulus that can create string stretch. The most dramatic case, however, occurred in a vertical well with a large tubing pump at high velocities where the simulations were interrupted halfway. Yet, the energy efficiency of the fibre rope system was as high, or even higher than that of the CSR in a slanted well with an insert pump, making it a viable option for wells where the dynamic liquid load in the tubing is not significantly high.

The wire rope, simulated in combination with special protectors, also proved its applicability as an SR string with the SRABS pump, with lower string stretch in contrast to fibre ropes. Although the energy efficiency of this system was the least of the three cases in the slanted well, it demonstrated a better performance than the fibre rope in the vertical well. This means that of the two techniques, pumping with wire rope is the better choice for extreme conditions. Although their energy efficiency may be less than the conventional designs, the benefits of their continuous structure can make up for the shortcomings in a long-term period.

There are still uncertainties with regard to some mechanical values, e.g. friction factor of the materials with steel. Fatigue and corrosion resistance and tensile strength of the strings also need to be measured at wellbore conditions to confirm their mechanical superiority to CSR’s. Incorrect values can lead to miscalculations of break load, contact force and system efficiency.

The advantages and disadvantages of wire rope and fibre rope systems, in conclusion, can be listed in Table 13:

	Advantages	Disadvantages
Wire Rope	• Lighter weight • Higher Tensile strength • No couplings • Reduced string damages • Increased MTBF • Simpler transportation and deployment • Adaptable to small footprint long-stroke units • Smaller counterweight requirements • Lower energy requirements	• Lower energy efficiency • Slightly lower production rate • Current cover is unsuitable
Fibre Rope	• Extremely light structure • Extremely high tensile strength • No creep • No couplings • Reduced string damages • Increased MTBF • Less contact force with the tubing • Simpler transportation and deployment • Adaptable to small footprint long-stroke units • Small counterweight requirements • Lower energy requirements • Better energy efficiency	• Lower effective stroke length • Lower production rate • Not applicable in severe pumping conditions • Temperature restrictions

Table 13. Advantages and disadvantages of wire rope and fibre rope systems at a glance

9 Recommendations

The provided thesis was carried out based on a novel idea of using a state-of-the-art wire and fibre rope as the sucker rod string. This applicability was simulated with an advanced software package that investigated the validity of this notion. However, the project was mainly aimed at analyzing the feasibility of such materials and is the first step of a long way to its real-life installation. The project contains initial knowledge related to the performance and requirements of these prototypes and therefore, in order to continue this investigation and arrange the field preparations, further research and experiments must be conducted. Below, some of the recommendations for future advancements of this project will be discussed.

9.1 Software Improvements

The practiced software package combines several MATLAB and Python codes while having a core in the interface of Abaqus. As the software is still in early stages of development, some features could not be altered to accommodate the alternative SR strings. These shortcomings were especially with regard to fluid flow effects on the continuous strings, something that needs to be modelled for each material, fluid and wellbore specification.

More analytical data obtained from rope manufactures or laboratory test in environmental conditions similar to that of a wellbore can also increase the precision of input data such as elastic or non-elastic behavior of the rope, friction factors and the appropriate surface unit since some values were inevitably extrapolated or assumed in this project.

9.2 Wire Rope Improvements

The selected wire rope, however high-end, should still be tested and modified specifically for pumping and wellbore conditions. It is also recommended to investigate the capabilities of other pre-stressed products of Voestalpine to find out whether or not any of them have an optimum performance. The following two suggestions are the most prominent to bear in mind:

9.2.1 Compacted String

Aside from the normal 7-strand wire rope, Voestalpine also manufactures compacted ropes from pre-stressed wires in different diameters. A compacted rope, as already explained in section 4.2.4, owns a greater cross-section area which makes it more similar to a solid rod. The reason lies in the construction of the rope as there is less empty space and higher contact area between the wires leading to a better distribution of stress among them. In addition, the company is able to provide a uniform cover with a cylindrical outer surface, allowing wellbore fluids to flow around it uniformly and without twist. The cover can be attached to the wire rope or move freely around it. Such alternative designs can be the subject of future researches on this project.

9.2.2 New Cover Material

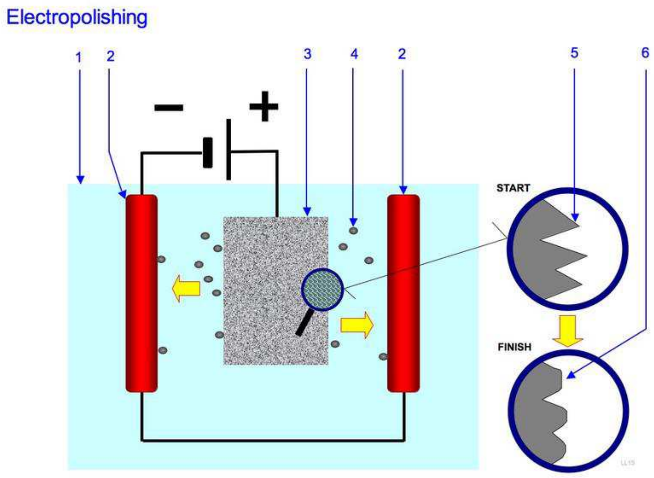
Wire rope jacket not only protects the wires from frictional damage, but also shields the string from corrosion and erosion as a result of H_2S and sand production. The temperature resistance is once again of utmost importance since a melting cover will not serve its installation purposes and can also complicate the reciprocating motion of the string. Additionally, it is likely that the applied wax between the wires reaches its pour point and causes the wires to rub against each other during the string movement.

The current polyethylene cover has been produced to protect wire rope in normal pressure and temperature situations and, as mentioned previously, is not strong enough to withstand the harsh environment of the wellbore.

Voestalpine has planned to set up and run its own unique coating and covering facilities within the next year. This will provide an opportunity to synthesize a special cover that fits the standards of wellbore applications. It is proposed that the wire rope, together with this enhanced cover, undergo laboratory tests in simulated environmental and load scenarios. A functional cover can significantly enhance the performance of the rope and the MTBF, and reduce the service costs.

9.3 Electro-Polishing

Electro-polishing is an electrochemical process performed to remove material from a metallic piece. It is mostly used to polish and passivate metal parts. In this technique, the metal piece is immersed in a temperature-controlled bath of electrolyte (most often concentrated acid solutions with a high viscosity, e.g. mixtures of sulfuric acid and phosphoric acid) and acts as the anode. It is therefore connected to the positive terminal of a DC power supply with the negative terminal being attached to the cathode. A current passes from the anode to the cathode, resulting metal on the surface to be oxidized and dissolved in the electrolyte. At the same time in the cathode, a reduction reaction occurs that normally produces hydrogen. Figure 48 shows a sketch of this process:



1. Electrolyte
2. Cathode
3. Workpiece to polish (Anode)
4. Particle moving from the workpiece to the cathode
5. Surface before polishing
6. Surface after polishing

Figure 48. Electro-Polishing process

Electro-polishing is very popular in the metal-finishing industry because of its simplicity and the possibility to be applied to objects of complex shape. A typical example is electro-polished stainless steel drums of washing machines. One of the benefits of electro-polishing for stainless steel is that it removes iron from the surface and enhances the chromium/nickel content for the most superior form of passivation for stainless steel [53].

The best and most practical scenario of using wire ropes is to deploy them without any extra subsurface components, meaning no protectors or cover. Nevertheless, the surface of the wires should be treated for resistance against friction, corrosion, erosion etc. Electro-polishing can therefore prove to be an effective treatment to prepare the wires for tough production conditions.

The total cost of any electro-polishing treatment is mainly driven by the amount of electrolyte solution required for the job. Although the operating costs, including equipment, labor and electricity, is around \$4.5 for each square foot of metal, the electrolyte solution will cost around \$25/gallon which can be quite substantial for large-scale polishing [54]. Such an investment requires a thorough consideration of factors like geometry of the well and the produced fines and fluids to confirm the necessity of an elector-polishing job.

9.4 Laboratory Tests on Fibre Rope

Dyneema® fibre's application in oil and gas industry is, for the time being, limited to mooring lines at offshore sites. For general purposes, using Dyneema® fibre won't go beyond towing trucks or yachting ropes either, where neither the performance nor the surrounding media is as demanding as a sucker rod pumping operation. This is primarily the reason for inconclusive test data that has been obtained only at low temperature and pressure experiment conditions.

Although the available data such as physical behavior, Poisson ratio and friction factor have been slightly modified for the performed simulations, it is still essential to find the exact values for these properties. The fibre rope must undergo multiple stress, friction and corrosion tests in wellbore conditions to observe the real behavior of the material and improve the predictions.

9.5 Design of Connections and Protectors

Previous attempts at deploying wire ropes as the sucker rod string have demonstrated that the weakest point of the system is still in the final connecting point at the bottom of the string to the pump. Preserving the tensile strength of the rope, replacing the corrosive connector pieces with resistant material and understanding the pump requirements are among the most essential factors when designing either a wire or a fibre rope system. Such a connection has recently been designed at the Chair of Petroleum and Geothermal Energy Recovery and can be seen with the wire rope itself in Appendix G – Voestalpine wire rope and connector.

Furthermore, special protectors which are easy to install and compatible to spooling is an important consideration point. Protectors should be light-weight, flexible and inexpensive to align with the goals of the project. It is also critical to calculate and decide on the number and location of these protectors along the rope to avoid over-weighting the string or complicating its movement.

Although the calculations can be performed with improved versions of the current software, laboratory and field testing would be extremely helpful in gaining accurate results.

9.6 Design of Surface Facilities

Sucker rod pumping systems using wire or fibre rope have special requirements concerning delivery and installation, spooling machinery, counterweight selections and possible service and workover units.

9.7 HSSE Considerations

Any innovation in the oil and gas industry has to clearly define its HSSE objectives and provide the regulations and execution strategies at the well sites. Both Voestalpine wire rope and Dyneema® fibre rope have been manufactured under to HSSE guidelines, however, their competency as part of an SR pumping unit under these regulations must still be evaluated. Design of the surface structure, transportation of components and the operation of machinery are in the top priority, especially in remote areas or brown field as uncertainties escalate.

All personnel need to be trained with the operational concepts of these systems and contingency plans have to be established in case of failure or accident. Such protocols have to be considered during and after the system design and can, therefore, be the topic of another research.

9.8 Economic Analysis

Estimation of the costs involved in a project is an integral part of conducting a business plan. For an innovative pumping system, comprising of unique surface and downhole components, such considerations can be summarized in the following categories:

- ✓ *Purchase*
- ✓ *Installation*
- ✓ *Maintenance*
- ✓ *Operation costs* (OPEX) e.g. electricity costs
- ✓ *Repairs*
- ✓ *Failure frequency*
- ✓ *Resale value* [1]

Experience has shown that novel ideas are not necessarily costlier than the existing technologies. The capital cost of a project is permissioned to be reasonably high if it prevents further repair costs and functions in a satisfactory manner for the lifetime of the well. This brings the necessity of conducting a financial analysis before the installation of a new system as a technology can demonstrate efficiency in one location and inefficiency in another.

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Appendix A – SRABS Setup Illustration

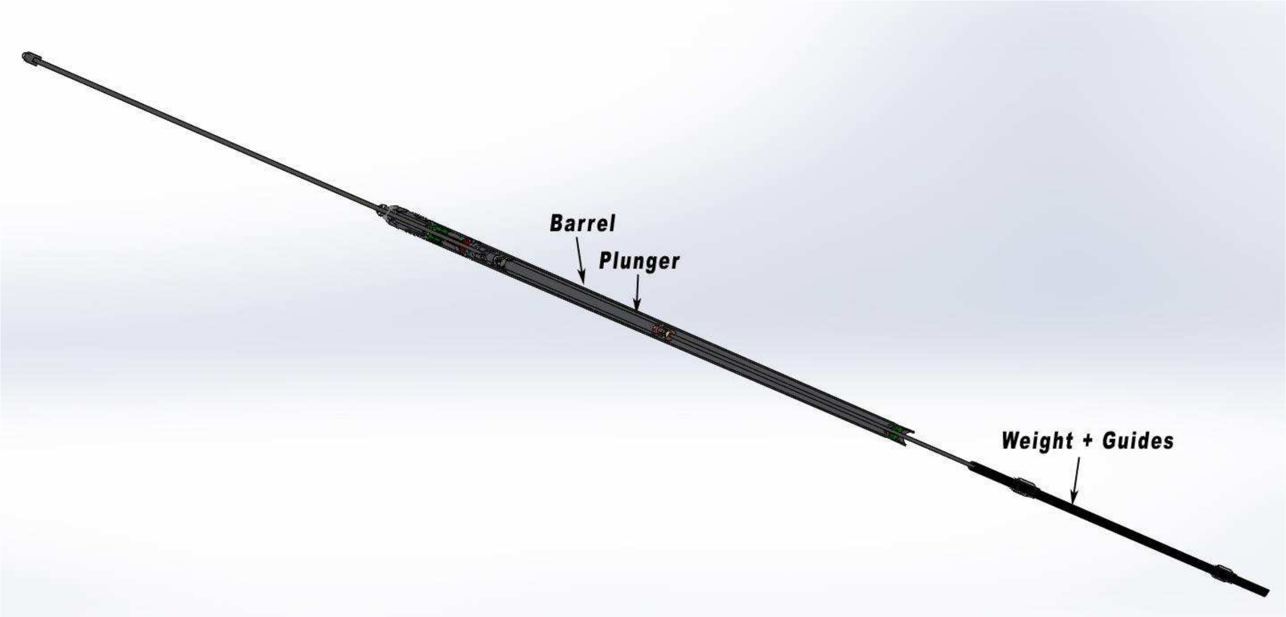


Figure 49. SRABS setup [50]

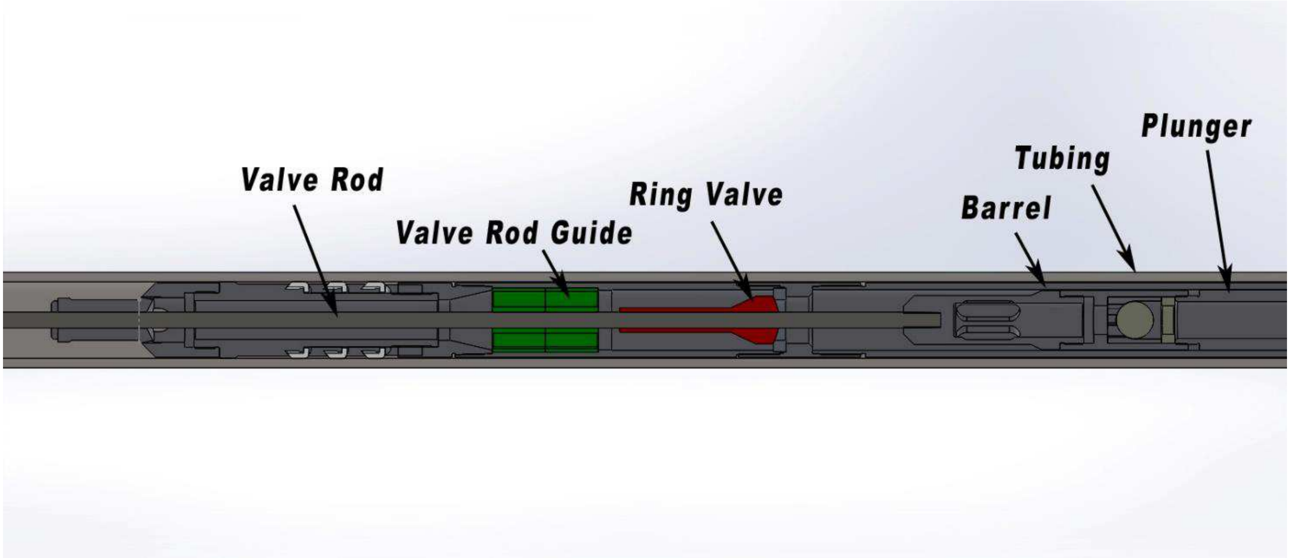
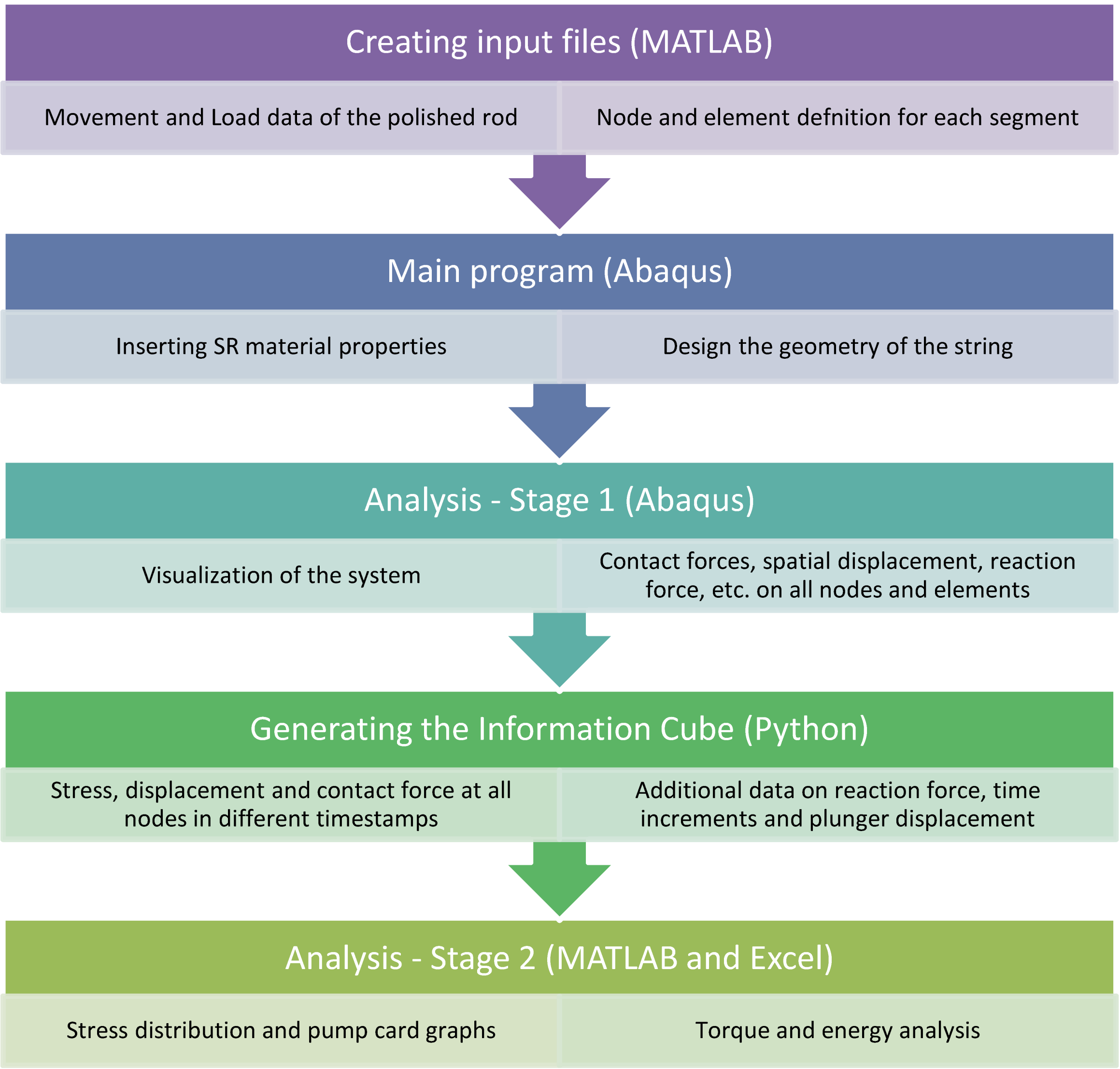
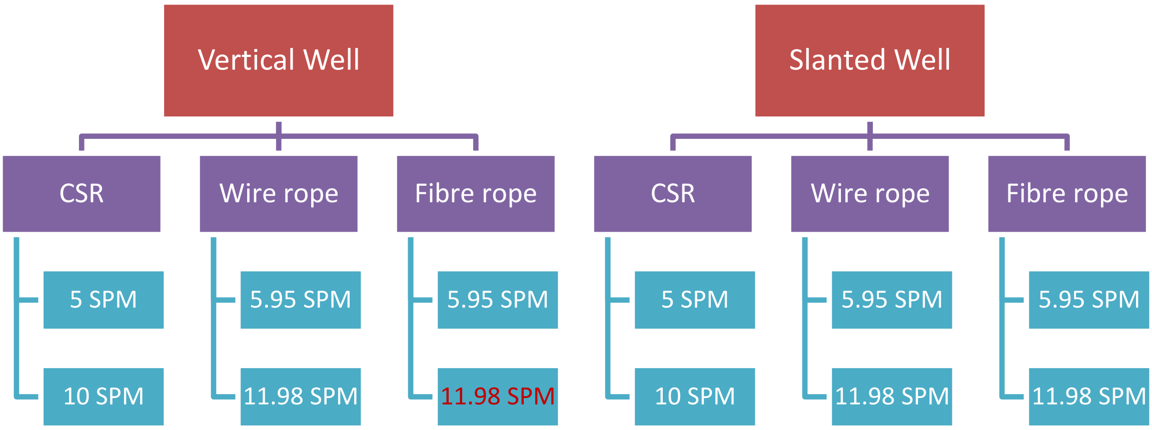


Figure 50. SRABS pump components [50]

Appendix B - Simulation Workflow



Appendix C – Simulation Cases



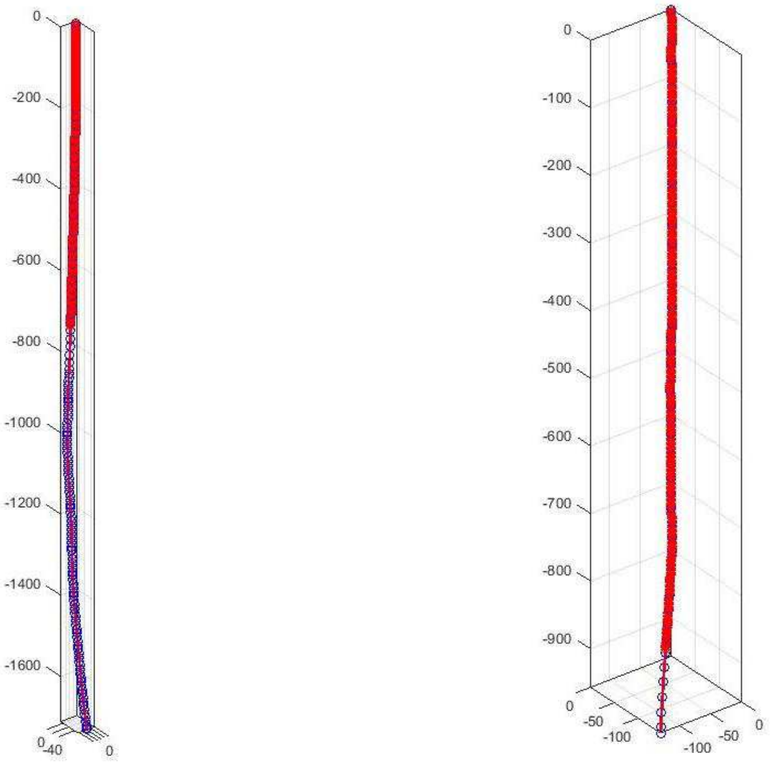


Figure 51. Geometry of the vertical well (left) and slanted well (right)

Appendix D – Load and Displacement Profile at Pump

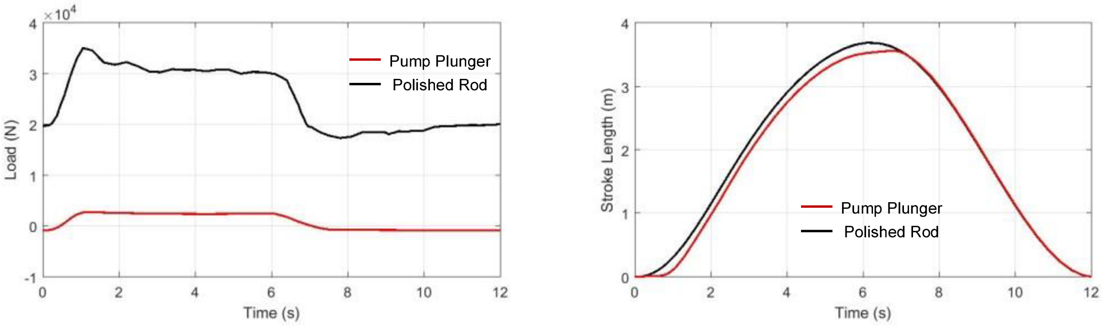


Figure 52. CSR in slanted well, low SPM

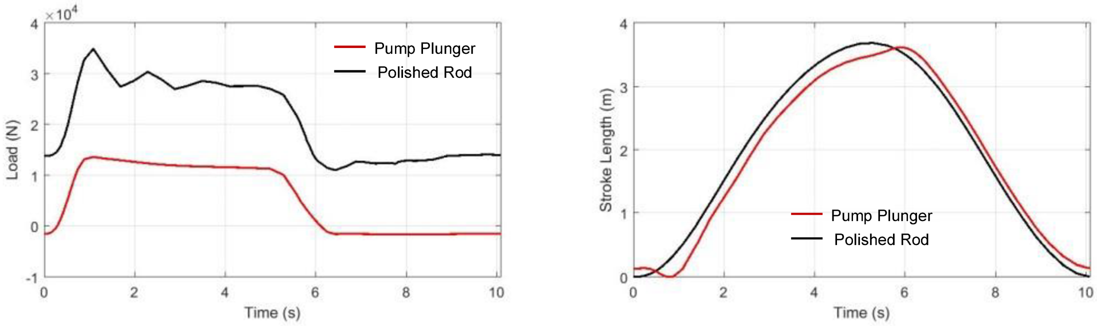


Figure 53. Wire Rope in slanted well, low SPM

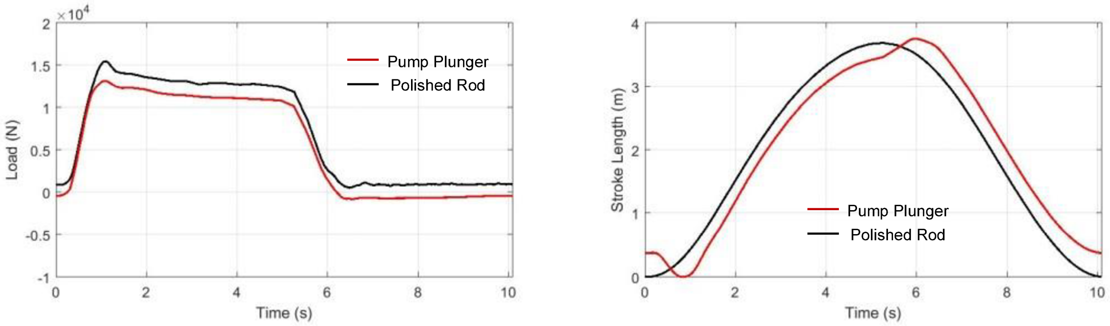


Figure 54. Fibre Rope in slanted well, low SPM

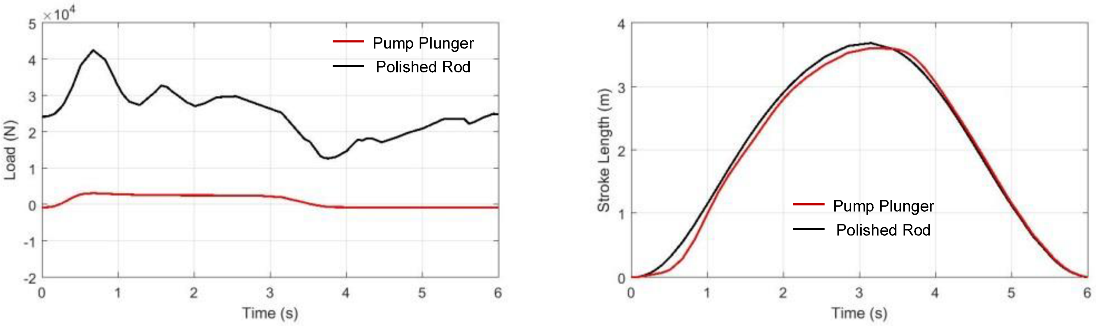


Figure 55. CSR in slanted well, high SPM

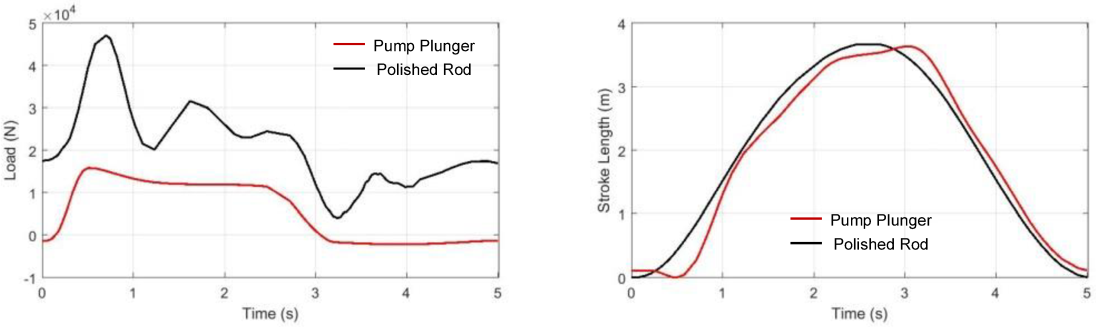


Figure 56. Wire Rope in slanted well, high SPM

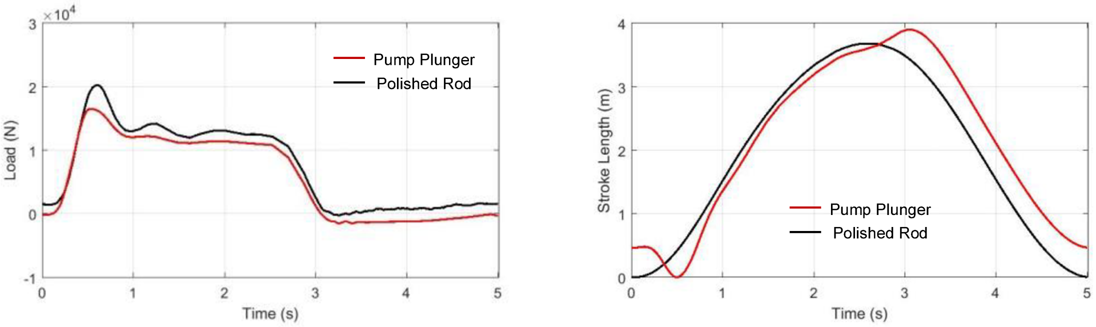


Figure 57. Fibre rope in slanted well, high SPM

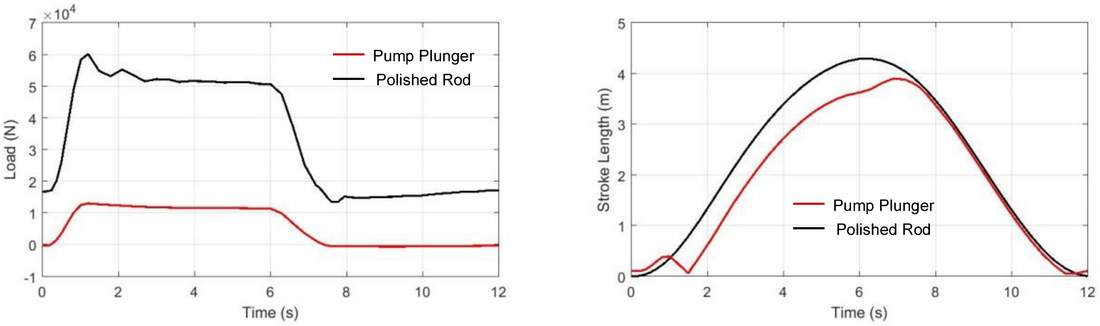


Figure 58. CSR in vertical well, low SPM

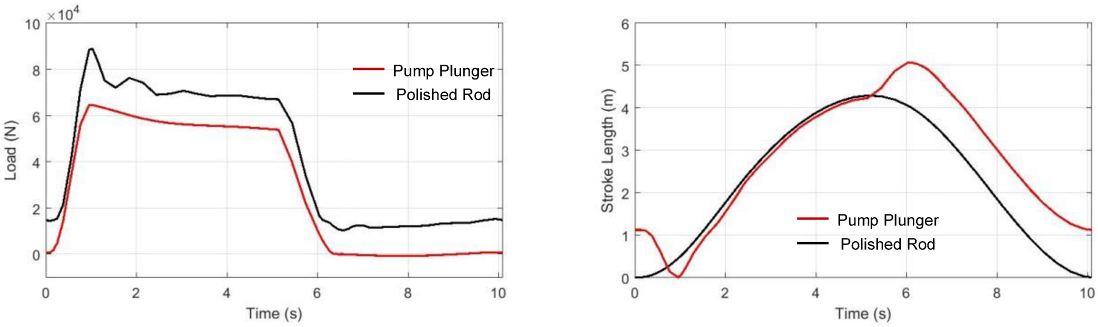


Figure 59. Wire Rope in vertical well, low SPM

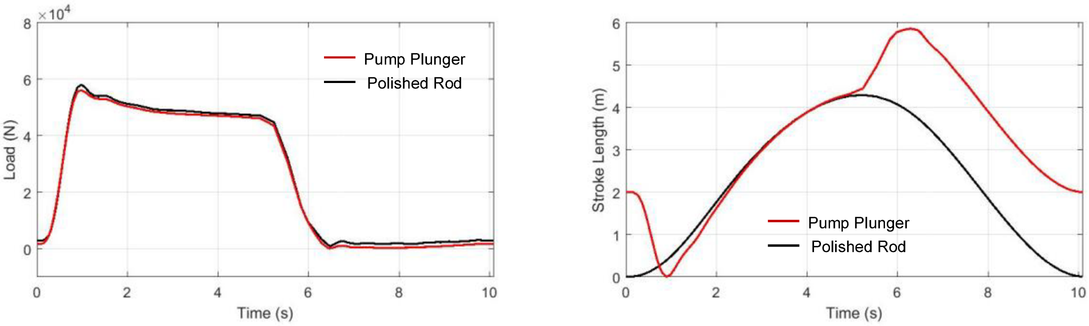


Figure 60. Fibre Rope in vertical well, low SPM

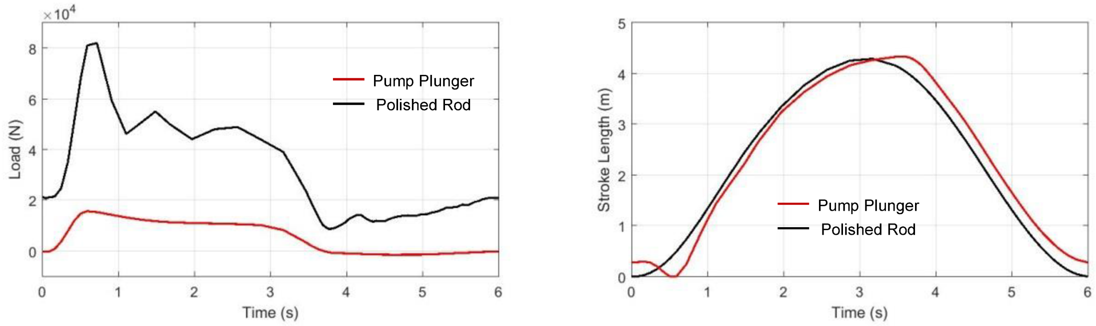


Figure 61. CSR in vertical well, high SPM

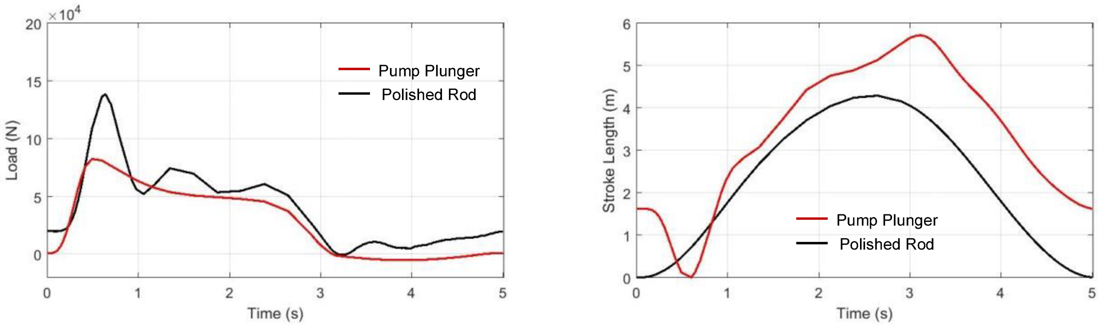


Figure 62. Wire Rope in vertical well, high SPM

Appendix E – Stress Distribution Graphs

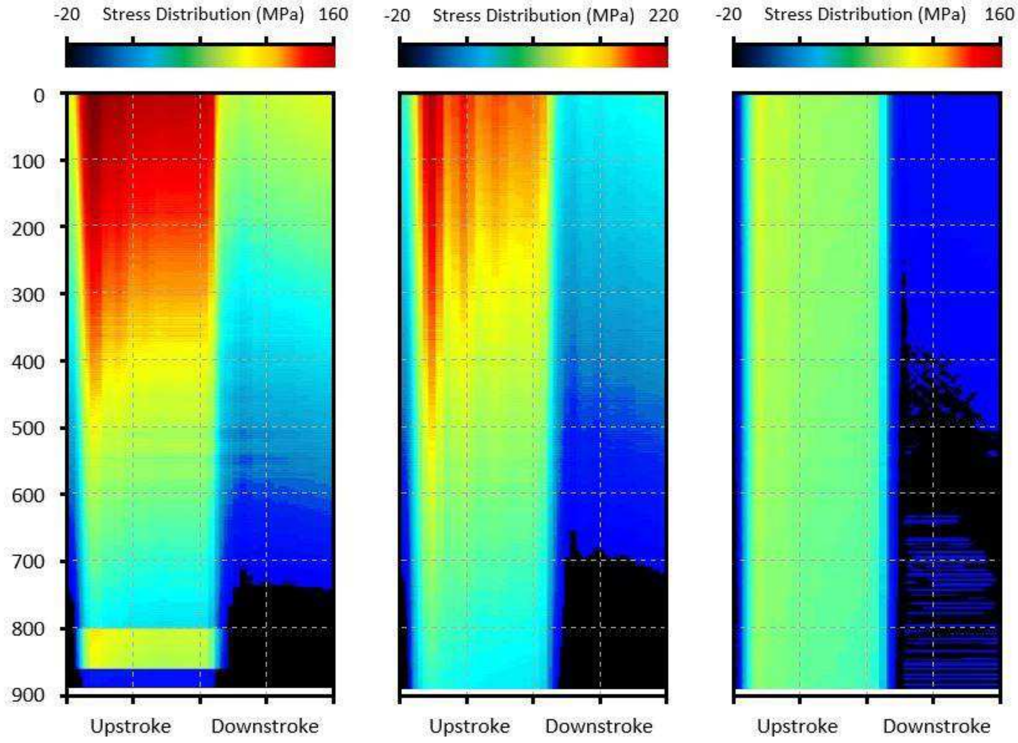


Figure 63. Stress distribution in the slanted Well, low SPM, from left to right: CSR, Wire Rope, Fibre Rope

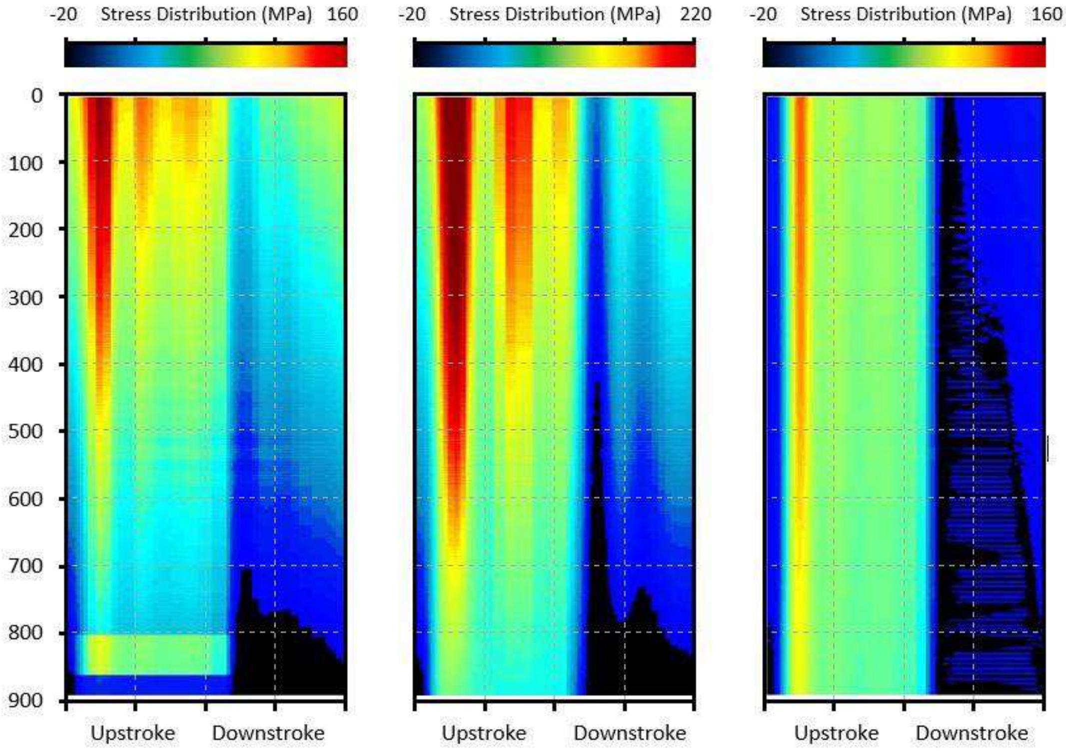


Figure 64. Stress distribution in the slanted Well, high SPM, from left to right: CSR, Wire Rope, Fibre Rope

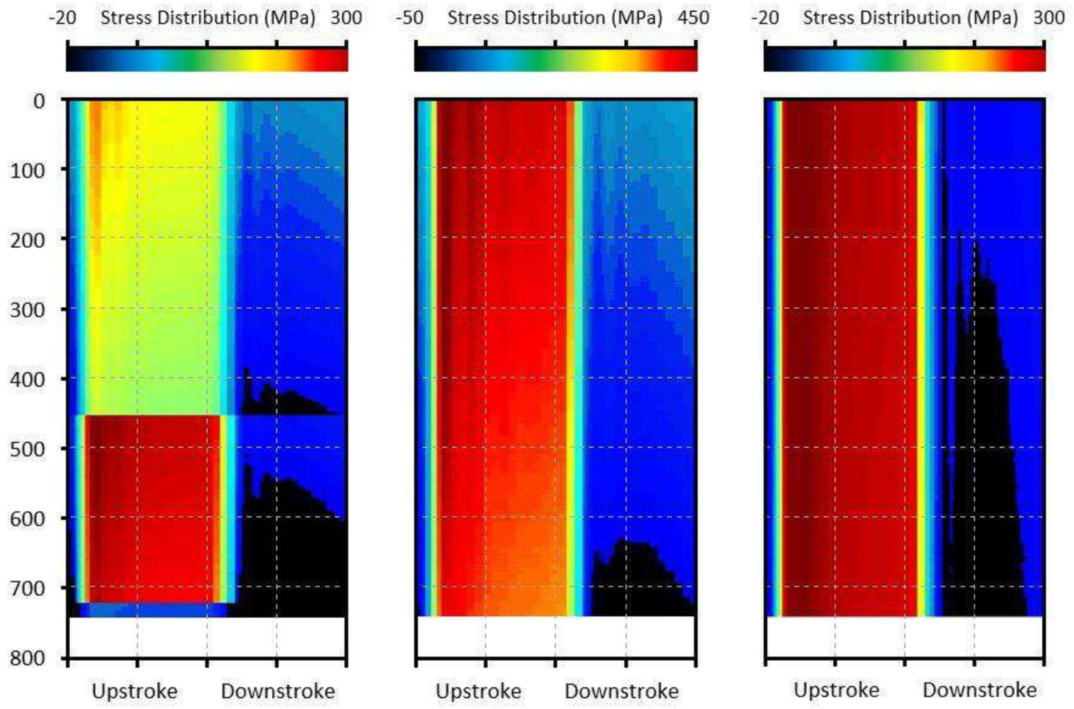


Figure 65. Stress distribution in the vertical well, low SPM, from left to right: CSR, Wire Rope, Fibre Rope

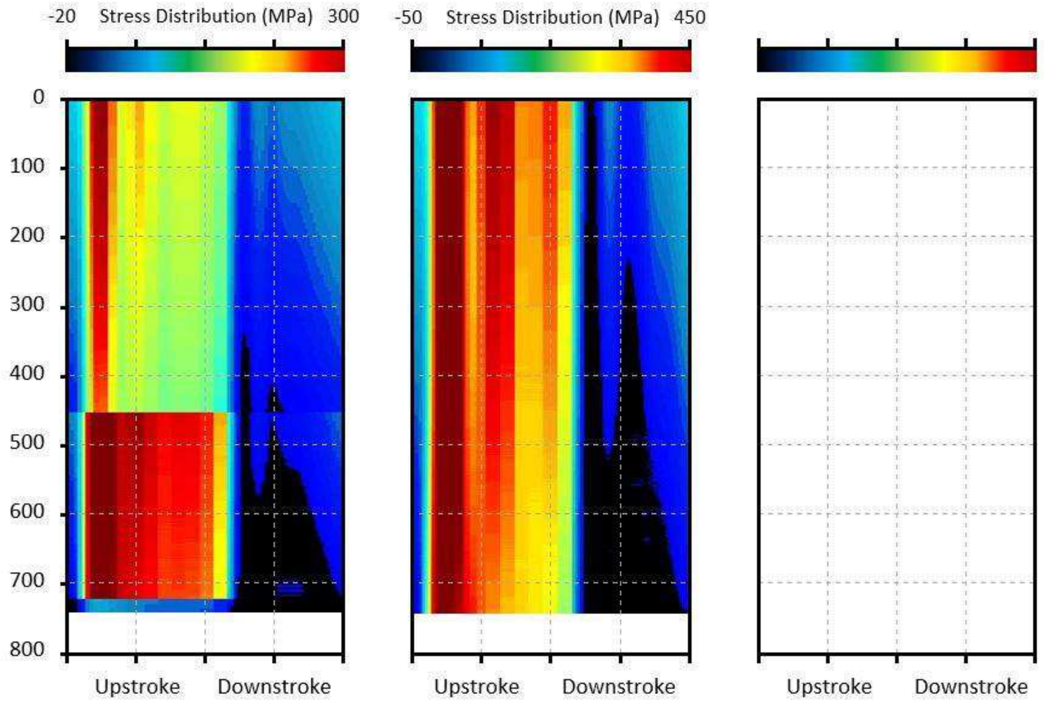


Figure 66. Stress distribution in the vertical well, high SPM, from left to right: CSR, Wire Rope, Fibre Rope

Appendix F – Torque and Energy Graphs

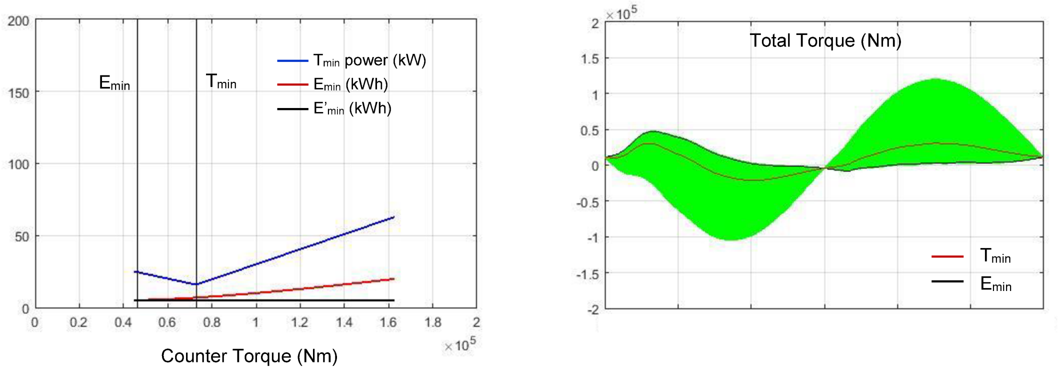


Figure 67. Torque and energy scenarios (CSR, slanted well, low SPM)

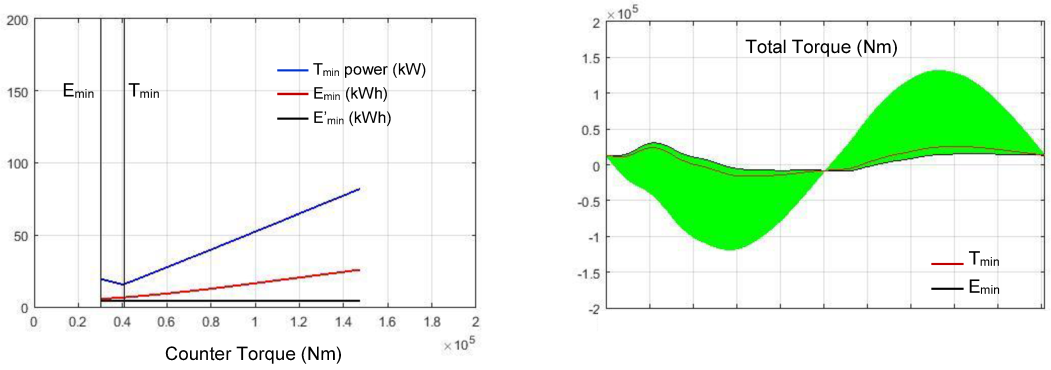


Figure 68. Torque and energy scenarios (Wire Rope, slanted well, low SPM)

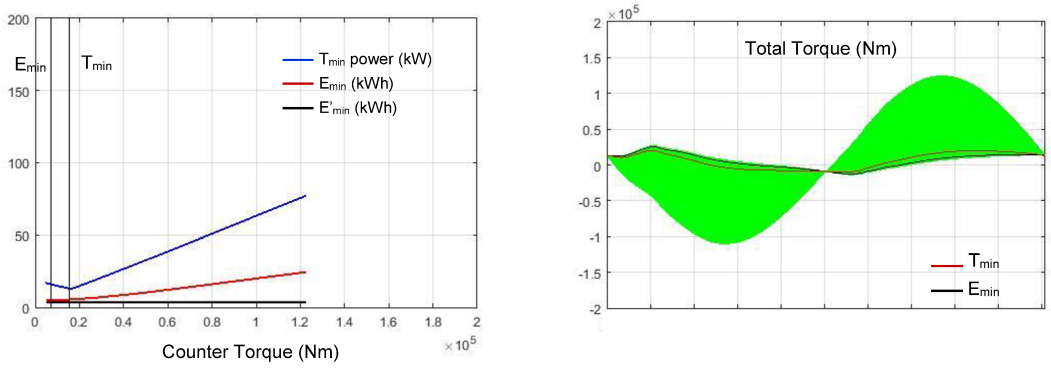


Figure 69. Torque and energy scenarios (Fibre Rope, slanted well, low SPM)

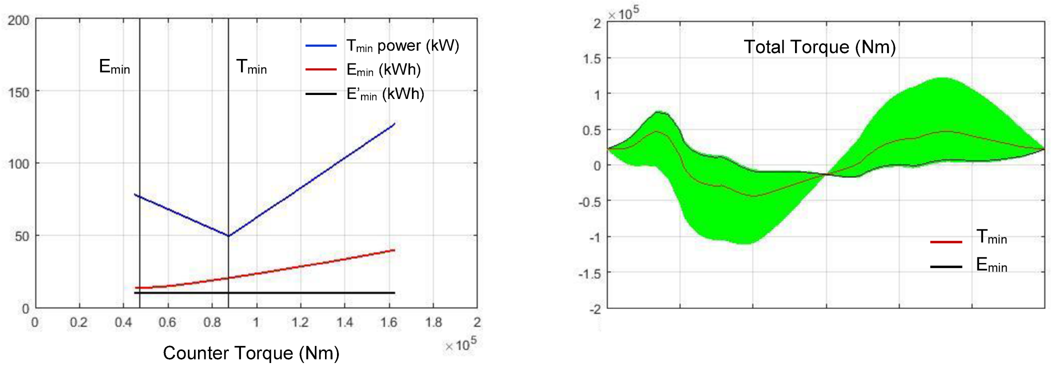


Figure 70. Torque and energy scenarios (CSR, slanted well, high SPM)

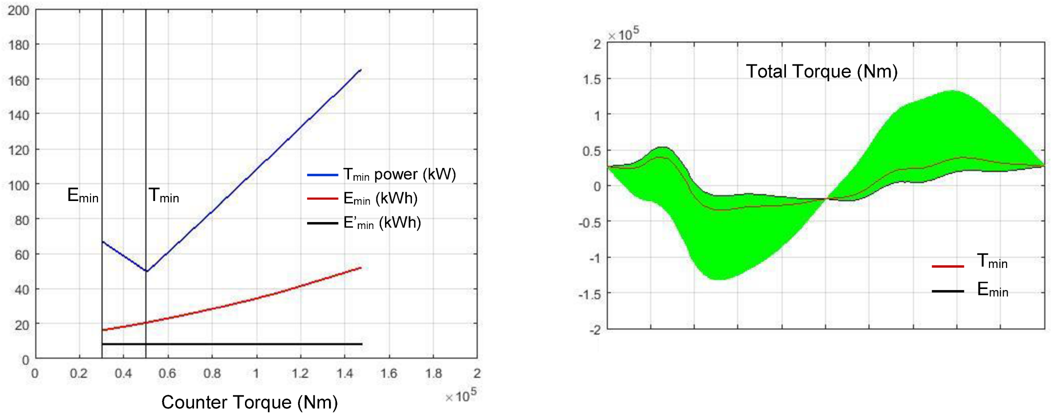


Figure 71. Torque and energy scenarios (Wire Rope, slanted well, high SPM)

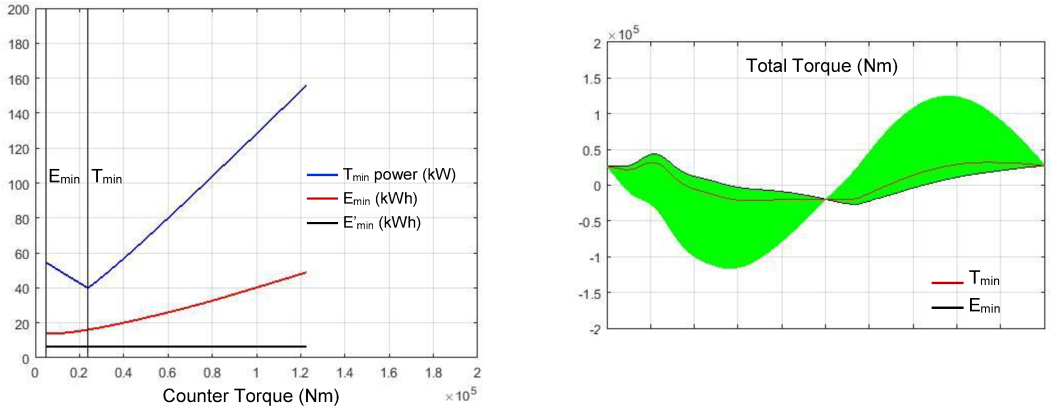


Figure 72. Torque and energy scenarios (Fibre Rope, slanted well, high SPM)

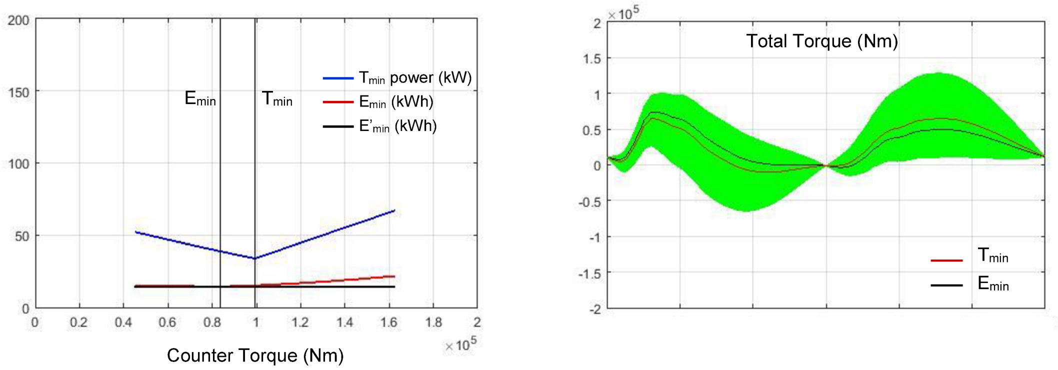


Figure 73 Torque and energy scenarios (CSR, vertical well, low SPM)

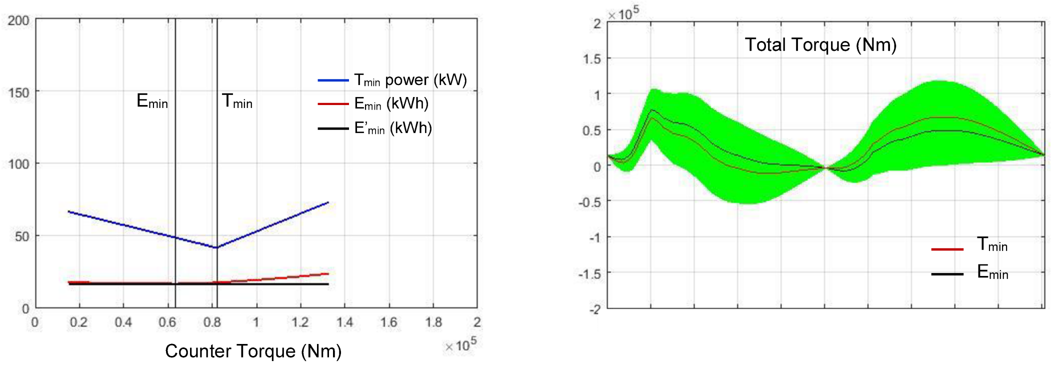


Figure 74. Torque and energy scenarios (Wire Rope, vertical well, low SPM)

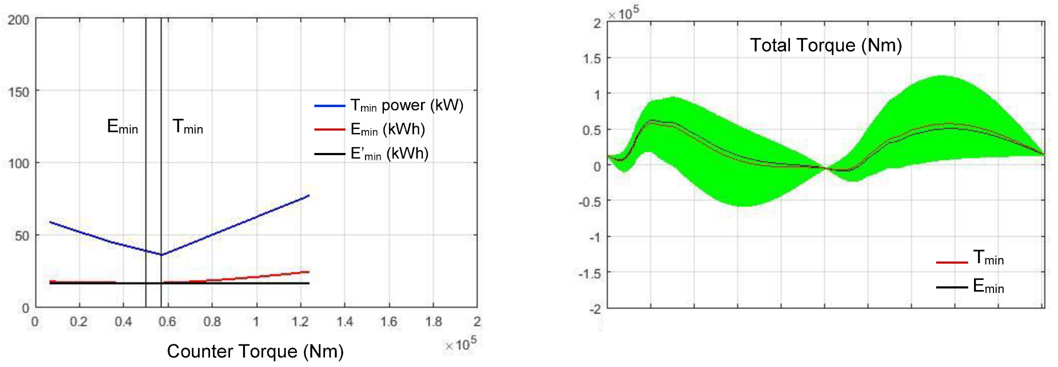


Figure 75. Torque and energy scenarios (Fibre Rope, vertical well, low SPM)

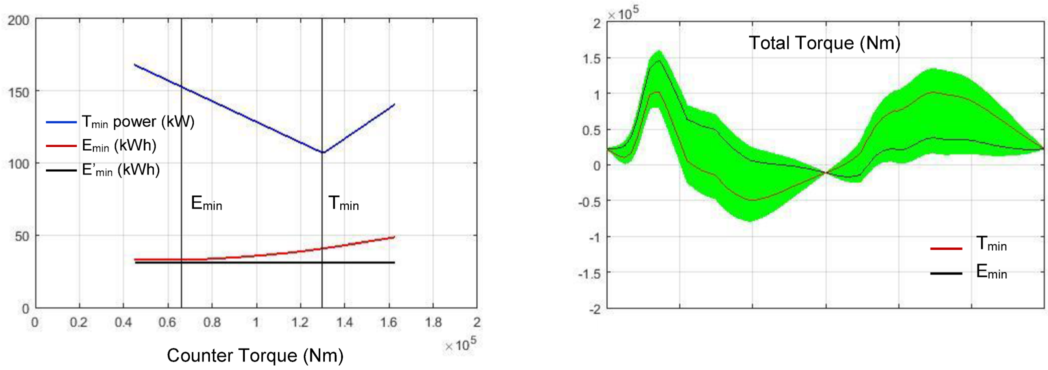


Figure 76. Torque and energy scenarios (CSR, vertical well, high SPM)

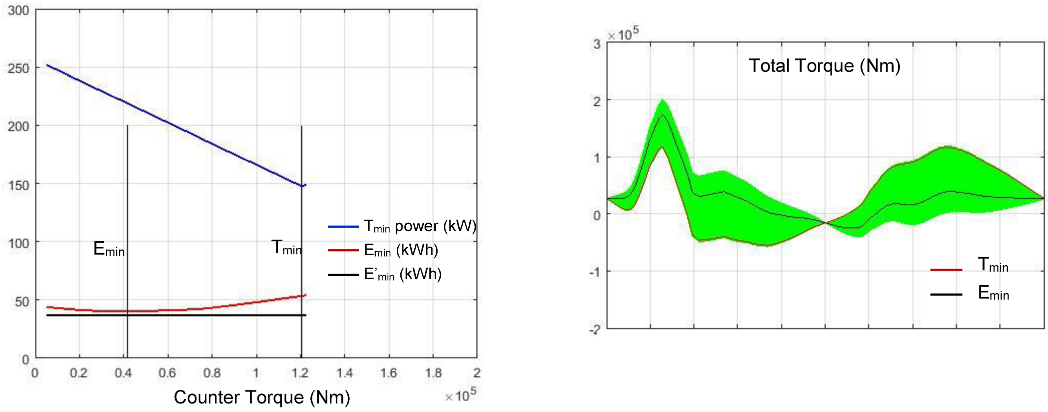


Figure 77. Torque and energy scenarios (Wire Rope, vertical well, high SPM)

Appendix G – Voestalpine wire rope and connector

Figure 78. Voestalpine wire rope and connector