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Desta, Yohannes Addis

ABSTRACT

As it is known, different maintenance and rehabilitation activities are conducted in oil & gas wells so as to ensure optimal flow rate, recovery volume, well safety and integrity. In doing all these activities, well intervention companies are highly dependent on the performance and reliability of wireline cables. However, senior technical people at Altus Intervention (formerly called Aker Well Service) have identified the presence of a miss-match between the performance of the currently available wireline cables (specially the 5/16″ - monoconductor cable) and the demand of a well intervention task as wells goes deeper, deviated, and acidic. For these reasons, the company has initiated this project work so as to look for the improvement potential of the currently used monoconductor cables.

In order to pinpoint the limitations of the currently used cables, I have conducted a thorough discussion with senior technical people at Altus Intervention, extracted relevant information and data from the company's Synergy page, participated in different wireline training courses, and also conduct relevant literature review. Overall, the inherent limitations of the currently used 5/16″ cables are found to originate from their limited strength, relatively heavy weight, integrity of the insulation material, and poor H_2S resistance of the steel (high strength version) armor. Moreover, operational related problems such as gas breakthrough, development of kinks and bird nesting, and also the cost of corrosion resistance grades of the cable are found to be leading problems. Thus, formulating a new design approach so as to address these limitations either fully or partially was the main theme of this project work.

In an attempt to solve these limitations, I have used a new design approach which effectively combines high strength Kevlar®49 fiber with abrasion resistance and electrical conducting steel armor wire. The new approach is found to have a higher prospect towards reducing the cable weight, improving the breaking strength, fatigue life, and alleviating short circuiting and other common problems of the currently used 5/16"- monoconductor cables. Furthermore, the conformance of the new concept cable to the harsh well environment, working condition, and operational demand of the well intervention task is also investigated using scientific data, mathematical modeling, software simulation, and other techniques.

Though all the results found are highly encouraging, I strongly recommend the development of a prototype cable and undertake all the relevant tests so as to review the conformance of the new cable to the actual working condition. Developing a tailored inspection technique for this concept cable and also extending the concept towards other cable grades are identified as continuation works of this project work. Furthermore, the possibility of finding non-steel based but abrasion resistance materials so as to fully replace the entire armor wire is also sighted as possible and fascinating research topic as this further helps to reduce the cable weight.

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1. INTRODUCTION

1.1. Introduction to Well Intervention Cables

As it is known, the useful life time of oil & gas wells could reach up to 25 years depending on the characteristics of the reservoir and production capacity of the operator. However, during this longer life time of wells, different maintenance and rehabilitation activities are conducted with the objective of ensuring optimal production rate, maximize recovery volume, safeguard well safety and integrity, and also for a safe plug and abandonment work. In doing all these, well intervention companies are highly dependent on the reliability and performance of both mechanical and electromechanical cables so as to execute activities such as perforation of the casing in the producing zone, opening or closing of valves, and other tasks deep in the well.

However, the rapid expansion of the oil & gas industry towards deeper sea floors and the practice of new and complicated well design approaches (e.g. deviated wells, horizontal wells) have stretched the capacity of the current cables to the limit. In addition to this, the presence of corrosive chemicals and gases such as H_2S and CO_2 in some fields and also the expected rise in the number of fields with these corrosive gases in the near future as more and more wells get depleted poses a different challenge. For these reasons, there is a quest for new well intervention cables with better performance as the currently available cables became unsuitable and problematic for well intervention companies.

As it is known, the well intervention industry currently uses cables of different size, strength, corrosion resistance, electrical property, and other operational parameters depending on the requirement of the specific well intervention jobs to be executed. Overall, well intervention cables currently available in the market could be categorized into two major groups, mechanical and electromechanical cables depending on the possession of electrical unit.

Mechanical Cables - cables under these category are primarily used for retrieving tools lost down hole(fishing job), lowering / lifting down hole equipment's, opening/closing valves , and other similar activities. Cables under this category are made of either a single wire (Slickline) or a bundle of several wires of different size and shape.

(a) 7/32″ Swabline *(b) 5/16″ Dycam*

Figure 1.1: *Typical Mechanical Cables* (Camesa, 2013)

Electromechanical Cables –this category of cables are used for jobs which require some sort of power supply, e.g. perforation, logging, and other similar activities and could be constructed either as monoconductor or multi-conductor of 3-7 conductor units in the core, as shown in figure 1.2 (a) and (b).

(a) 5/16″ - Monoconductor Cable (b) 7/16″-Multi Conductor

Figure 1.2: *Typical Electromechanical Cables (Camesa, 2013)*

As seen from figure 1.2 (a) and (b), a considerable portion these cables cross section is used to lay the copper conductors and the associated insulation layer. This in turn makes these cables less strong but more problematic than mechanical cables of the same size. Due to this, most of the problems reported are associated with cables under this category and it is also the keen interest of Altus Intervention (formerly called Aker Well Service) to investigate the improvement potential of cables under this category, and specifically the 5/16″ - monoconductor cable. Thus, this project work is also focused mainly on the 5/16″ - monoconductor cables though the new design approach we are going to discuss could also be easily adopted to other size and type of electromechanical and mechanical cables.

1.2. Statement of the Problem

The producing zone of some oil & gas fields are located several kilometers under the sea floor and it could also have horizontal deviation of significant length. For example, one of the wells in Åsgard (Q2) has a registered total length of 6,115m and from which 1375m exist in the deviated part. In this type of wells, the suspended weight of the cable by itself consumes most of the allowable working strength of the cable and leaves a limited working corridor for the tool string, friction with the casing, and possible stack of the tool string in some necked cross sections or other bottle necks.

Moreover, a snap of the cable at the tool head or breakage of the strands in mid-way will lead to a drop of the tool string down the well and create unnecessary additional and cumbersome work (tool retrieval or fishing) job. Events of such sort also lead to loss of production from the operator’s side and the well intervention company could incur not only additional operational cost but also a fine from the operating company for the unnecessary delay. Overall, depending on the geometrical complexity, depth, presence of significant H_2S concentration, high temperature and high pressure, cables currently in the market could be less reliable and unsuitable to handle the job both safely and cost effectively.

Based on my discussion with senior engineers, technical personnel’s and the company’s Synergy (company’s web page where incidents are registered) page, typical problems inherent to the currently used 5/16″ monoconductor cables are summarized as follows.

1.2.1. Strength of the Cable

The product catalogue found from CAMESA cables rate the average nominal breaking strength of the most commonly used 5/16″ monoconductor cable (1N32) in the order of 53.3KN. Besides this, the manufacturers recommended working range of the cable is limited to 50% of its breaking strength. Furthermore, the limited strength of the cable becomes more evident if we notice its weight, which is known to be 288 kg/km in air or 238 kg/km in water (Camesa, 2013).

Moreover, the presence of corrosive gases (typically H_2S) will force well intervention companies to use corrosion resistance cables (e.g. 1N32 S77) which is known to have up to 14.8 % less breaking strength than regular cables of the same size. This implies, the presence of H_2S in deeper and deviated wells will make the problem even worse and make the well intervention task more challenging.

In these types of situations, naturally one could think about the use of cables with larger diameter (e.g. 7/16″) though this is not always the case as seen in figure 1.3. The problem here is that, the wellbore pressure generated force acting upwards exceeds the downwards force with a value proportional to the cross sectional area of the wireline. As a result, though increasing the diameter of the cable obviously increases the tensile string, the associated increase in the cross sectional area generates a large upward lifting force and will demand a heavier sinker for vertical wells and also a heavy duty tractor to pull the cable for deviated and horizontal wells, which all will have its own challenges and operational demands both to drive into the well and to come out of the well.

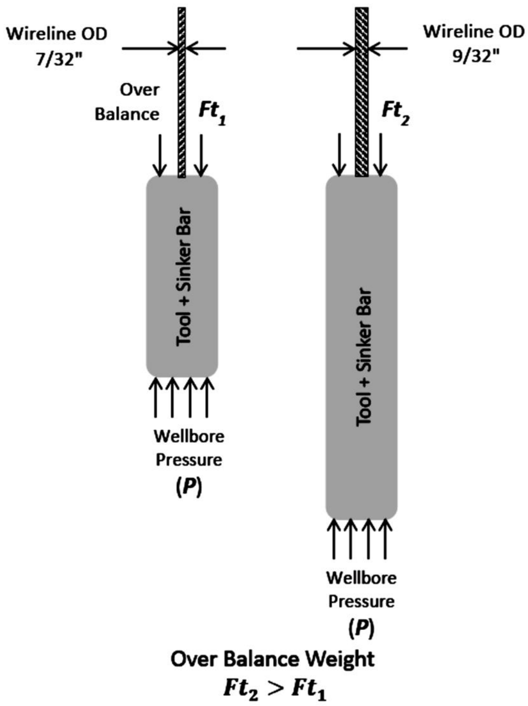


Figure 1.3: *Comparison of Cables with different size* (Dunning, 2013)

In general, the smaller the cable diameter, the easier and the faster the cable sinks downwards and it is also becomes easy to come out of the well at the end of the job. Moreover, controlling high pressure gases at the grease stuffing box where the cable comes out from the producing tubing will also be easier for smaller diameter cables as the clearance between the wire and the grease injection box orifice becomes relatively small. *Overall, the allowable working strength of the currently available 5/16" mono-conductor cables could be considered sub-optimal and unsuitable to some jobs currently at hand and expected in the near future.*

1.2.2. Weight of the Cable

For materials used in cable and rope construction, a typical comparison parameter called characteristic length is often used as it relates strength and weight at the same time. Characteristic length refers the maximum freely suspended length a material could support before it fails from its weight. In this regard, steel wire rope with a characteristic length of 19km stands last in comparison with aramids and carbon fiber according to a scientific report published by Rebel (2005).

Currently used cables (e.g. 1N32 S77) have a rated weight in the order of 294kg/km in air or 243 kg/km in water (Camesa, 2013). Theoretically, a cable with a unit weight of 294kg/km consumes 2.88KN of its strength for every 1km of the cable suspended in air or if we take a well with an effective vertical height of 4km, the weight of the cable alone will consume 11.54 KN or 50.82 % of the allowable working strength of the cable. This in turn leaves us with a limited operational window depending on the depth of the well, geometrical configuration, and it has become a common practice to compromise the recommended safety margin (50%) set by the manufacturers. *In summary, the weight of the currently used cables is considered relatively heavy and any improvement on the cable weight will have the same effect as improving the breaking strength of the cable.*

1.2.3. Sour Gas Resistance of the Cable

In reality, wireline cables are not expected to last extremely long due to the severity of the working environment and as a result, the impact of normal surface corrosion is not a significant problem as the wires are usually galvanized. However, exposure of regular steel cables to H_2S and CO_2 gases could deteriorate the cable performance within a very short period of time and make the cable much weaker than the rated strength. H_2S and CO_2 gases have the potential to react with the coating (zinc) of the armor wires and gradually penetrate to the lattice structure of the steel armor and result in hydrogen stress cracking (HSC) and Sulfide stress cracking (SSC) which both makes the wire to behave as brittle as glass rods according to Moffat et al. (2012).

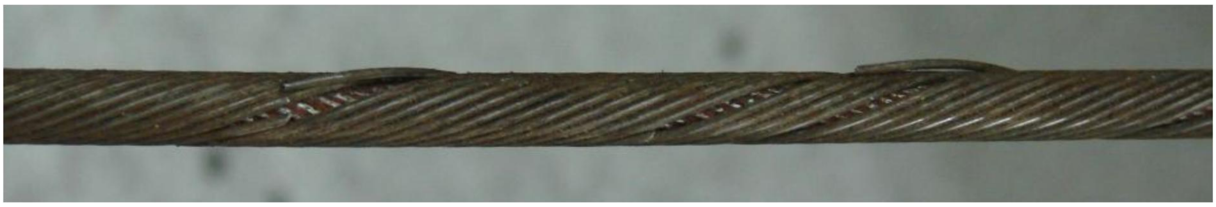


Figure 1.4: *Broken Armor wires from H_2S embrittlement* (Moffat et al., 2012)

In the current practice, Altus Intervention use stainless steel grade cable for sour wells with H_2S concentration in excess of 10%. However, the strength of stainless steel cables currently in use (5/16″ mono-conductor cables) is up to 14.8 % lower than regular steel cables and this presents a challenge much worse than regular steel cables. Moreover, the current market price of stainless cables is also found to be 8.5 times more expensive than regular steel armor cables according to the data found from the company’s procurement department. *In general, their higher cost and limited strength of H_2S resistance cables make them a bitter alternative at the moment and any improvement made on this category of cables will have a much more significant effect than regular steel cables.*

1.2.4. Electrical Related Issues

In the case of monoconductor cables, the inner copper wires and the outer armor wires serve as a complete electrical circuit. As a result, the steel armor serves not only as a load bearing element but also as a current return path. The steel armor of currently used cables have a resistance rating of 6.9Ω/km or 36.7Ω/km for regular steel cable and stainless steel cables respectively. The main difference in resistance between the two cables is associated with the relatively high resistance of the alloying elements used in stainless steels. According to senior technical personnel’s at Altus Intervention, the desire armor resistance for smooth operation is in the order of 10Ω/km though operation could be conducted up to 36.7Ω/km or slightly higher.

In addition to this, damage of the insulation material as the armor wires squeeze the insulation with the copper conductors and the associated short circuiting related problem is also found to be a major setback of currently used cables. Moreover, the copper wires are also reported to buckle and cut the insulation layer during operations in the range of 60% of the cable strength. This problem is associated with the difference in elastic limit of steel and copper which the latter sustains a significant residual plastic deformation while the steel wires regain their elastic stretch leading the copper wires to buckle and dig through the insulation layer. Overall, there is a room for improvement in the electrical property of the currently used cables mainly the short circuiting related problem.

1.2.5. Gas Break Through

During operation, the valley between any two adjacent armor wires is sealed circumferentially with a high pressure grease and often there are incidents where pressurized gas escape to the platform. Moreover, increasing the grease stuffing pressure will lead to over loading of the cable as extra force is required to pull the cable at the winch. In reality, the effort required to seal highly pressurized gases at the grease stuffing box is highly dependent on the smoothness of the cable which in turn depend on the diameter of the armor wires. *In this regard, minimizing the size of the armor wires will have a positive effect towards reducing gas breakthrough related incidents while operating high pressure wells.*

As a summary, there exists a miss-match between the job demand and performance of the currently available 5/16″ - monocodncutor cables and investigating the limitations of the currently used cables in detail and generating a feasible solution to address these problems is the main goal of this project work.

1.3. Project Objectives

As outlined in section 1.2, there is a gap between the job demand and the performance of currently available 5/16″ monoconductor cables. Thus, ***generating a new cable design approach to address the limitation of the currently used cables is the main research objective of this work***.

Moreover, this project work has also the following goals:

- **Improve the Breaking Strength of the Cable** - as the main limitation of the currently available cable lays on their relatively limited strength, looking for the means to address the problem has been given a due attention.
- **Reduce the Weight of The Cable** - reducing the weight of the cable has the same effect as increasing the tensile strength of the cable. As a result, the new design approaches developed in this work has taken this fact into consideration.
- **Increase the H_2S and SO_2 Resistance of the Cable** - Sulfide Stress Cracking (SSC) is presented as one of the serious problem incurred in the currently used cables (regular steel cables). Thus, the new design approach presented in this work has attempted to address the problem and without compromising the cable strength as the case of currently used cables.
- **Alleviate Short Circuiting Related Problems –** as electrical short circuiting is found to be a typical problem, the new design approach presented in this project work has tried to address the problem at a significant level.
- **Improve the Useful Life Time of The Cable** - The life time of the cable is associated with its fatigue resistance, aberration wear resistance, and the integrity of the electrical conductors, the inner and outer armor and also the insulation layers. As a result, the new design approach has investigated the best way of improving the cables useful lifetime.
- **Minimize Gas breakthrough Related Incidents –** as such incidents pose operational risk, the potential of the new design approach to address these issues is also dealt in depth.

1.4. Methodology and Approach

In order to achieve the objectives we set on section 1.3, different tasks are identified and executed throughout the projects life span. The tasks performed range from identifying the limitation of the current cables to alternative solution generation and could be summarized as follows.

- **Literature review** - Literatures related to wireline cables, aramid ropes, corrosion of sour gases, fatigue and abrasion wear of cables, the impact of elevated temperature on the mechanical and chemical property of common cable and rope materials are studied in depth. Moreover, the science of rope and cable construction, new developments in the cable and rope design, and other relevant literatures are also investigated and summarized.
- **Participated in wireline trainings courses -** In order to understand the process of the well intervention job, I have participated in three wireline and logging related courses at Altus Intervention (formerly called Aker Well Service Academy).
- **Data Collection and Information Gathering -** Information and data sources such as senior technical personnels in the wireline intervention business, the Synergy webpage of the company, cable catalogues, and cable manufacturer's information help desk, relevant and disclosed patents, and other sources are utilized so as to understand the practices, operational parameters, and the deficiency of the currently used mono conductor cables.
- **Analysis and Problem Definition**- based on the interpretation of the information and data collected, key operational deficiency of the current cables are identified.
- **Generate Alternative Solutions -** Based on identified problems, potential intervention spots are identified and a range of alternative solutions are formulated and investigated.
- **Feasibility Assessment -** The alternative solutions proposed are investigated and a detailed analysis is conducted so as to assess the improvement potential of the individual concepts. The assessment was mainly based on improvement potential of the cable in tensile strength, weight reduction, addressing electrical related problems, sour gas related problems, etc. Moreover, possible changes required at the operational level, manufacturability of the cable, the estimated cost of the new cables and other factors are also considered during the feasibility study.
- **Software Simulation** - Selected design concepts are further developed and investigated with the help of wireline simulation software (Cerberus) and the outputs from the software are used so as to assess the expected performance and make comparison with the existing cables.
- **Presentation and Discussion** - The preliminary results and achievement from the new design approaches are summarized and presented to both technical and management personnel's of Altus Intervention. The feedbacks and concerns gathered from the presentation are utilized to further improve the design concept under investigation.
- **Technical Report Writing** - a technical report which summarizes the methodology and the achieved results is compiled and made available to Altus Intervention and University of Stavanger.

2. LITERATURE REVIEW

2.1. New Developments in Rope and Cable Design

As it is known, human civilization and technological advancement has a strong correlation with the discovery and utilization of materials. For example, a long time demand of light, stronger, and corrosion resistance structural materials from the aviation industry has been recently answered with the discovery and commercialization of carbon fiber. As a result, we could consider Boeing's new product (787 - Dreamliner), as a typical case to shown how advancement in the material science led to significant improvement in existing technologies and products.

In the same manner, recent developments in the production of high strength synthetic polymer fibers (Aramids, Glass fiber, Carbon fiber) at a commercial scale has presented new opportunity towards lighter, stronger, and corrosion resistance ropes and cables. *The main inspiration idea of this thesis work could also be traced back to the reported achievement of some researchers in the design and manufacturing of new composite cables for the mining industry.* A research paper published by Rebel et al. (2005) claimed that, up to 20% weight reduction and 30 % increase in the load capacity was achieved on 48 mm diameter and 3000m long hoisting wire rope by incorporating high strength aramid fibers as shown *in figure 2.1.*

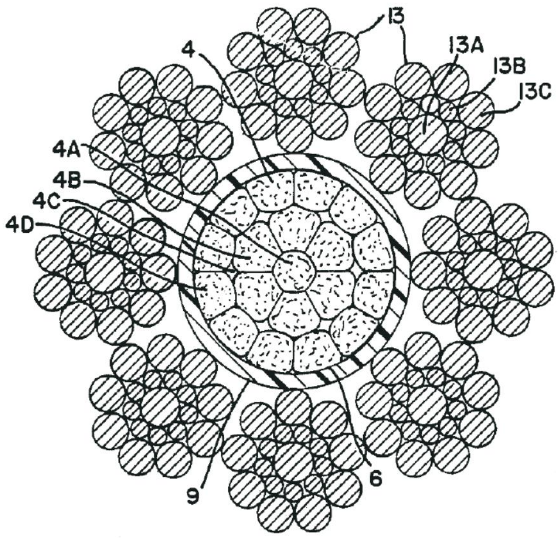


Figure 2.1: *Composite steel wire rope (*Rebel et al., 2005)

For cables of significant suspended length, the main design concern will be either to reduce the weight or to improve the breaking strength while maintaining the diameter of the cable constant. Though synthetic ropes enable us to achieve a good combination of strength and light weight, their poor abrasion property limits their application as stand-alone hoisting cable materials. To alleviate this shortcoming, the use of at least one layer of metal armor wires as shown in *figure 2.2* is recommended and practiced by several researchers and manufacturers.

Figure 2.2: *Sample composite cable developed by CASAR (Rebel, 2012)*

The use of synthetic fibers in the design and manufacturing of plain ropes, heavy duty electrical cables, and fiber optic cables is a matured and well known practice with hundreds of different products already available in the market. Typical products currently available in the market which could be considered as a success in substituting the heavy weight and the poor corrosion resistance cables include:

- Mooring systems of offshore platforms
- Intercontinental fiber optic cables
- Bridge suspending elements
- Antenna anchoring units, etc.
- Umbilical tethers, etc.

In general, the use of high strength fibers in the construction of cables and ropes with the objective of reducing the weight of the cable without compromising the strength of the cable is a new direction. *Consequently, it is also my strong belief that, aramid fibers, especially Kevlar®49 could be used as a strengthening member in the construction of well intervention cables on condition that the harsh oil & gas well environment and operational requirements are fully understood and properly addressed.*

2.2. Prospects of Kevlar® 49 as Cable Strengthening Unit

Kevlar is a para-aramid synthetic fiber developed in the 1965 for the first time by a Polish scientist working for DuPont (Kevlar Aramid ® fiber, 2013). Kevlar with a density of 1.44g/cc, possess an incredible strength in the order of up to 5 times the specific strength of steel and also exceptional thermal stability to a wider temperature range (Kevlar Aramid ® fiber, 2013). Moreover, the presence of Aramid molecules as liquid crystals in a solution makes the synthesis of long and parallel chains relatively easy and practical (Burgoyne, 1993).

Aramid fibers are made of long benzin rings having additional carbon and nitrogen atoms in between the consecutive benzene rings. These parallel and long chain Kevlar fibers achieve their strength through cross linking of the hydrogen bonds. The extra atoms (carbon and nitrogen) support the oxygen and hydrogen atoms respectively to form a weak but multiple hydrogen bonds between the adjacent chains (Burgoyne, 1993). In general, properties of Kevlar fiber vary with the denier value, the typical Kevlar fiber filament it possess (e.g. Kevlar® 29 or Kevlar ®49). Since Kevlar and other aramid fibers are composed of hairy fiber filaments, the textile nomenclatures (Denier and Tex or decitex(dtex)) is often used. The definition and the relation between denier and decitex are as follows.

- Denier is the weight of a 9000 meters filament of a fiber whereas ,
- Tex is the weight of a 1km of a yarn, and 1Denier = dtex x 0.9.
- Typical Kevlar®49 filament diameter is 0.00047 inches or (12 microns)

Figure 2.3: *Kevlar Yarn in its natural colour* (Shanyou Londtai Plastic Products co., ltd)

For Kevlar® 49 fiber to be a potential candidate as well intervention cable strengthening unit, it has to satisfy some of the key demands of the job. In doing that, a detailed literature review of Kevlar fibers in line with the well intervention operational requirement and working environment has to be conducted. Once the different properties of Kevlar are analyzed and compared with typical cable and rope materials such as steel, carbon fiber, glass fiber, technora, and twaron, it will be possible for us to decide if the fiber could be considered as a potential candidate material or not.

In order to evaluate the potential of Kevlar fibers as well intervention cable material, typical evaluation parameters such as strength, high temperature property, chemical resistance, fatigue life time, stiffness, abrasion resistance, cost of the material, electrical property, availability and maturity of the technology to change high strength fibers into cables of several kilometers is dealt in detail an presented in the next sections.

2.3. Mechanical Properties of Kevlar ® 49 Fiber

In order to characterize the mechanical properties of materials, typical criteria's such as tensile strength, stress-strain behavior, fatigue life, abrasion and wear resistance, stiffness, and hardness are commonly used. However, some of these properties (e.g. tensile strength, fatigue life, and stress - strain behavior) are much more important for cable and rope construction than typical properties such as hardness. As a result, we only discuss some of the mechanical properties which will have direct effect on the performance of the end product.

2.3.1. Strength of Kevlar® 49 Yarn

Undisputedly, there exist barely few materials at a commercial level with a tensile strength higher than Kevlar® 49 as we could see from table 2.1. Kevlar® 49 fiber with a tensile strength of 3600Mpa is almost double the strength of common steel wires of 1960Mpa ultimate strength though it is impossible to manufacture a Kevlar rope of 3600 MPa breaking strength. Comparing Kevlar fiber and steel wire taking their density in consideration make Kevlar® 49 much more stronger (5 times) than steel wires. As it is known, carbon nanotubes are currently in research and development phase and commercialization of this product is not expected at least in the near future.

Table 2.1: *Mechanical Property of Candidate Materials (*Rebel et al., 2005)

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

In addition to tensile strength, the other two key evaluation criteria's (fatigue resistance and abrasion resistance) make Aramid fibers (Kevlar, Technora, and Spectra) novel rope and cable material compared to glass and carbon fibers as indicated on table 2.2. However, Aramid fibers perform badly in relation to heat and chemical resistance which we will discuss in detail on section 2.4 and 2.5 respectively.

Table 2.2: *Comparison of common fiber materials (Christine, 2014)*

	Glass	Aramid	Carbon Fibre
Cost	Excellent	Fair	Poor
Weight to Strength Ratio	Poor	Excellent	Excellent
Tensile Strength	Excellent	Excellent	Excellent
Compressive Strength	Good	Poor	Excellent
Stiffness	Fair	Good	Excellent
Fatigue Resistance	Good-Excellent	Excellent	Good
Abrasion Resistance	Fair	Excellent	Fair
Sanding/Machining	Excellent	Poor	Excellent
Conductivity	Poor	Poor	Excellent
Heat Resistance	Excellent	Fair	Excellent
Moisture Resistance	Good	Fair	Good
Resin Adhesion	Excellent	Fair	Excellent
Chemical Resistance	Excellent	Fair	Excellent

Remember these ratings are relative to each other. Not to all materials.

Unlike steel, the compressive strength of Kevlar is only 20% the tensile strength and considered unsuitable material for applications where significant compression strength is required *(Burgoyne, 1992)*. In reality, the compression stress expected on cables and ropes is limited to the suspended weight of the cable if any slack exists and Kevlar ® 49 with strength of 300Mpa is not expected to suffer due to its light weight.

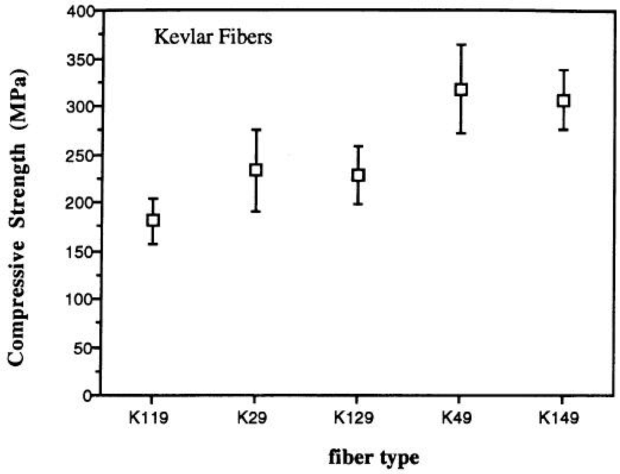


Figure 2.4: *Compressive Strength of the different Kevlar fiber categories (Fahey, 1990)*

As we could see from figure 2.4, Kevlar is traded in several names and for different purposes. However, two of the most common high strength fibers for the rope and cable construction are limited to kevalr®29 and Kevlar ® 49, where Kevlar® 29 is the forerunner. The difference in mechanical property of the two fiber categories could be understood from table 2.3.

Table 2.3: *Properties of para-Aramid fibers (Chang, 2011)*

Material	Density, g/cm^3	Filament diameter		Tensile modulus(a)		Tensile strength(a)		Tensile elongation, %	Available yarn count, No. filaments
		µm	µin.	GPa	10^6 psi	GPa	10^6 psi		
Kevlar 29 (high toughness)	1.44	12	470	83	12	3.6 2.8(b)	0.525 0.400(b)	4.0	134–10,000
Kevlar 49 (high modulus)	1.44	12	470	131	19	3.6–4.1	0.525–0.600	2.8	25–5,000
Kevlar 149 (ultrahigh modulus)	1.47	12	470	179	26	3.4	0.500	2.0	1,000

(a) ASTM D 2343, impregnated strand (Ref 16). (b) ASTM D 885, unimpregnated strand (Ref 17).

From table 2.3, we could understand that, Kevlar® 49 is the strongest fiber with fiber strength in the order of 3.6 - 4.1 GPa. Whereas, Kevlar ®149 possesses ultra-high modulus and strength but limited fiber length and considered unsuitable material for rope construction, according to *Chang (2011)*. In general, high strength, limited elongation, and other factors make Kevlar®49 the preferred cable material though Kevalr®29 is also widely for its marginal cost advantage.

2.3.2. Stress - Strain Behavior of Kevlar Fibers

Stress - strain behavior is an important evaluation criterion to assess the % elongation and dimensional stability of materials in response to an applied load. The criteria becomes much more important for ropes and cables of several kilometers long since the % elongation could be significantly large and pose a main problem in the integration of the different units (e.g. copper conductors, steel armor, insulation layers, etc.) of the cable. As seen from figure 2.5, Kevlar® 49 has limited elongation to failure compared to steel wires. This property is usually considered as advantageous for long ropes and cables, while a significant elongation to failure is a required property for short cables as the energy absorption capacity of the cable is dependent on its elastic and plastic elongation capability.

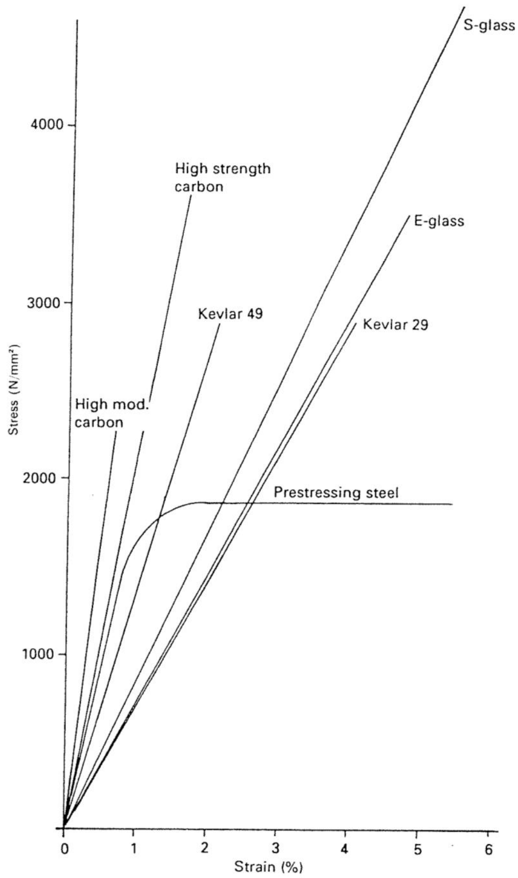


Figure 2.5: *Typical stress –strain curves for aramid and some comparable alternative materials (Burgoyne, 1992)*

From figure 2.5, we could understand that, the elongation of Kevlar®49 fiber is slightly higher than steel wires within the practical working stress range and this in turn leads to a significant challenge in the design of composite cable of steel armor and Kevlar fiber units. To address the problem, either extra load has to be transferred to the steel armor or a geometrical configuration to ensure extra stretchability to the steel wires has to be materialized.

2.3.3. Fatigue Life of Kevlar Fibers

Fatigue failure is one of the root causes of failure in steel ropes and no wonder if we consider the property as a potential evaluation criterion to assess the candidacy of Kevlar yarn. Fortunately, Kevlar yarn registers a much better fatigue life than steel since failure in Kevlar is from the cumulative damage of stress-rupture instead of the usual number of cycles as defined for steel and other materials *(Burgoyne, 1992)*. For this reason, fretting related fatigue failure in Kevlar fibers is only seen at the termination points (connection ends) where one fiber glides over the other *(Burgoyne, 1992)*.

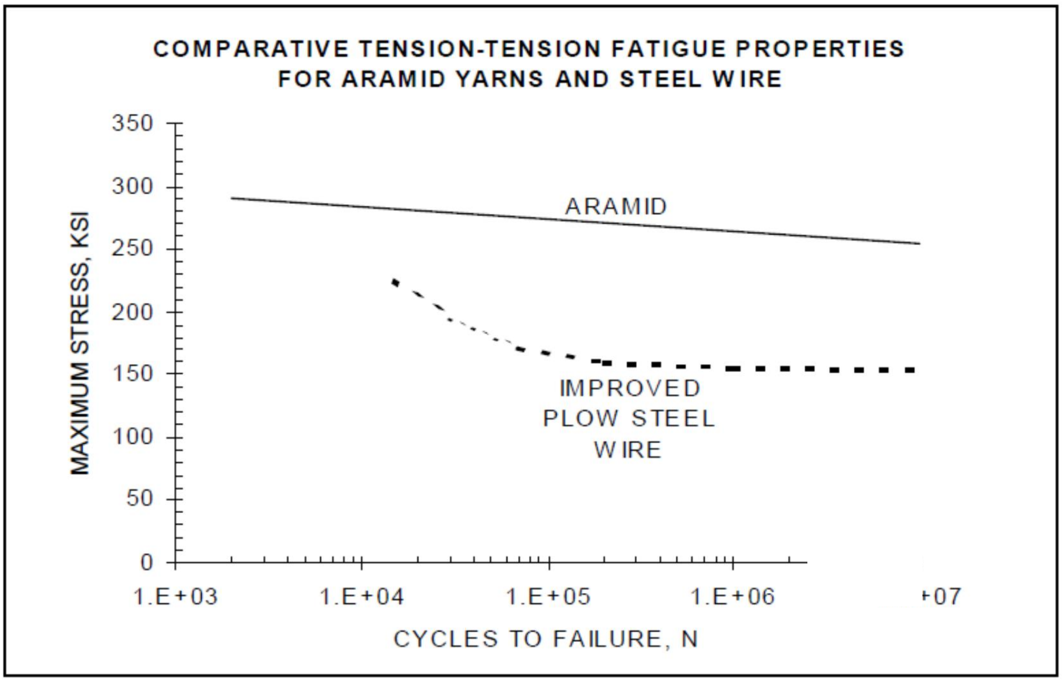


Figure 2.6: *S-N curve for tension-tension fatigue fracture of Kevlar yarn (*Heisler, 1998)

As seen from figure 2.6, Kevlar® 49 and Kevlar® 29 in a non-twisted lay have a better fatigue life than steel wires even at a higher stress level and could be considered a suitable material for the design and construction of cables and ropes.

2.3.4. Wear and Abrasion Resistance of Kevlar Fibers

Mechanical wear and abrasion resistance property of materials define their hardness to deter any scratch and eventual worn out of the material by foreign objects or similar objects gliding one over the other. In this regard, well interventions cables are subject to a significant wear and abrasion not only on the sheaves and sliding friction between inner and outer armor wires but also the friction wear from deviated and horizontal wells, necked cross sections, grease stuffing box, etc.

Unlike of steel, Kevlar is not wear and abrasion resistance and this property limits the application of Kevlar as a stand-alone cable material under exposed condition. However, compared to glass fiber, carbon fiber, and the other Aramid materials (Technora, Twaron, and Spectra), Kevlar has an excellent abrasion and wear resistance property according to the comparison conducted by Christine (2014).

2.4. Elevated Temperature property of Kevlar ® 49

The effect of temperature on the mechanical property of Kevlar fiber is a main concern as the temperature of oil & gas wells could be reach as high as 200 ^{0}C in some specific wells. As a result, assessing the high temperature of Kevlar in relation to loss of strength with temperature, thermal expansion or contraction, and creep property will have a paramount importance.

2.4.1. Loss of Tensile Strength and Retention Property of Kevlar

Kevlar fiber unlike of other traditional polymer materials didn't soften, ignite, or catch fire upon heating (Kevlar Aramid® Fiber, 2013). In fact, this property has make Kevlar to be the preferred fabric for clothing of fire-fighters, escape chutes in oil platform, and other similar flame resistance applications. However, Kevlar lose its tensile strength significantly at a temperature in excess of 204 ^{o}C and considered unsuitable material for extra high temperature applications. For example, Kevlar®29 heated at 250^{0}C for an extended period of time could lead up to 50 % of its strength though this loss is recoverable up on cooling to normal operational temperatures (Kevlar Aramid® Fiber, 2013).

Fortunately, the thermal conductivity of Kevlar fibers is too low and ropes with a larger diameter or insulated could survive a temperature as high as 300^{0}C for several hours without losing a significant portion of their strength according to the same source, Kevlar Aramid® Fiber(2013). As most of the experimental results published are conducted under the presence of atmospheric air, the high temperature performance of Kevlar under a sealed environment is not known at large. However, the absence of oxygen and nitrogen obviously will impede the decomposition reaction and I expect a much better resistance though this argument couldn't be supports at this moment of time.

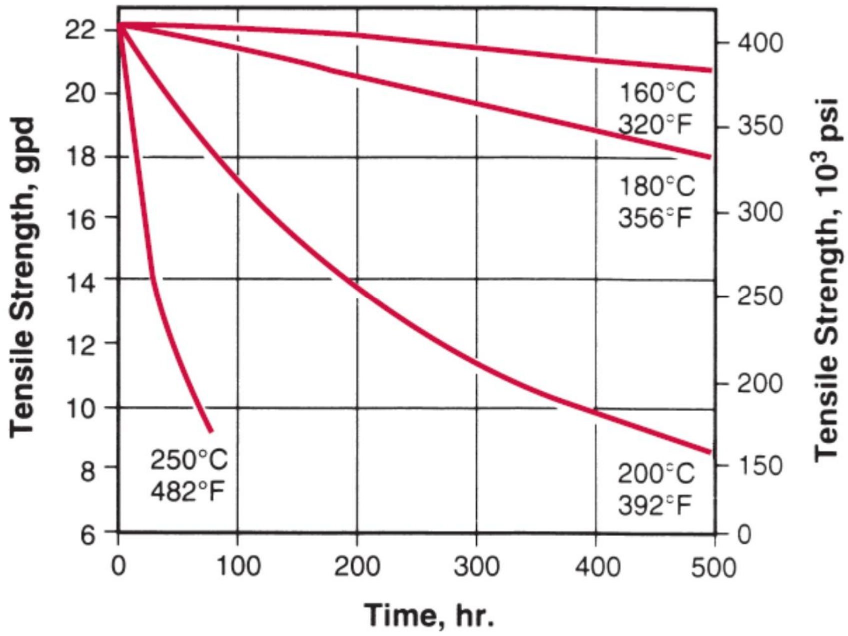


Figure 2.7: *Impact of elevated temperature on the tensile strength of Kevlar ® 29yarns* (Kevlar Aramid® Fiber, 2013)

As referred by Kevlar®49 exclusive manufacturer, Du Pont, Kevlar fibers could be used up to 177^{o}C for a continuous 100 hours without noticeable loss of tensile strength. For cables used in the well intervention operation, the exposure time per run is limited to few hours and as a result, noticeable deterioration of Kevlar within the temperature range of most wells is not expected. However, Kevlar based cables could be concluded as unpractical for few of the extra high temperature wells found in different parts of the world.

The graph shown in figure 2.7 is conducted under the presence of air and is also based on Kevlar® 29 yarn and doesn't necessary describe the high temperature vs. strength property of Kevlar® 49. Though most of the experimental results are conducted on Kevlar ®29, its successor is widely seen to possess a relatively better performance in most parameters and taking this value as threshold limit will not be a problem.

The other interesting property of Kevlar fiber is related to its strength retention property by which the material claims back any lost strength as a result of exposure to elevated temperature. Practically, this property is exceptionally useful in the cases where deployment is mandatory for wells in the order of 200 ^{0}C or slightly above. As we could see from figure 2.8, exposure of Kevlar ® 49 at 300 ^{o}C in air for up to 12 hours and cooling to room temperature will result in reduction of strength only by 20%. However, a longer exposure time is seen to have a significant adverse effect on the strength retention property of Kevlar fibers.

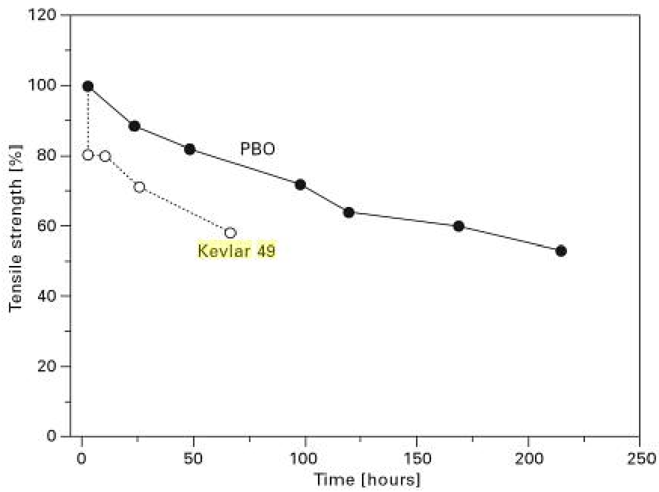


Figure 2.8: *Strength Retention of Kevlar® 49 fiber Vs time (at 300 ^{o}C in Air) (Bunsell, 2009)*

2.4.2. Dimensional Stability of Kevlar Fibers at Elevated Temperature

Expansion or contraction of Kevlar fibers at elevated temperature is also a point of interest as significant expansion or contraction will induce the same effect as stress – strain behavior we discussed on section 2.3.2. The temperature of most oil and gas wells is quite high and to assure the conformance of the high temperature property of Kevlar and the working environment is our main priority. If the fiber is not dimensionally stable with temperature, the percent elongation of the cable could be significant and the integration of the fiber with the other elements of the cable could be lost easily and lead to failure of one ahead of the other.

However, as we could see from the figure 2.9, the effect of elevated temperature is largely on the tensile strength and as a result the strain-stress curve is more or less similar to room temperature property. As temperature gets higher and higher, the fiber gets weaker and weaker while the modulus of elasticity is more or less unaffected. Moreover, unlike of steel which has a positive coefficient of thermal expansion (CTE), Kevlar has a negative CTE. As a result, Kevlar shrinks slightly with a CTE value shown in the table 2.4.

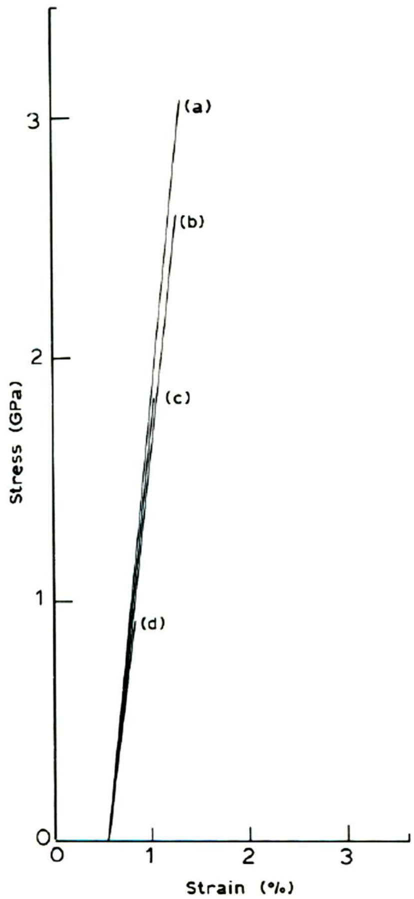


Figure 2.9: *Stress - Strain curve of Kevlar filaments at different Temperatures (*a) at room temperature (b) thermal exposure at 150^0C (c) at 250^0C (d) at 350^0C (Parimala et al.,1993)

In general, Kevlar didn't decompose up to 427 ^{0}C and also didn't become brittle or shrink as low as -196^0C (Kevlar Aramid® Fiber, 2013). Overall, Kevlar could be considered as dimensionally stable material within the expected working temperature range of most oil and gas wells.

Table 2.4: *Coefficient of Thermal Expansion* (Kevlar Aramid® Fiber, 2013)

Type of KEVLAR®	Denier	Temp. Range °F (°C)	CTE in./in./°F (cm/cm/°C)
KEVLAR 29	1500	77-302 (25-150)	-2.2 x 10[illegible] (-4.0 x 10[illegible])
KEVLAR 49	1420	77-302 (25-150)	-2.7 x 10[illegible] (-4.9 x 10[illegible])

*Tested with zero twist and 0.2 gpd tension at 72°F (22°C), 65% RH.

Since wireline cables are meant only for a limited time of service, properties such as creep is not as such significant property though creep value of Kevlar is in the order of 0.8% for 50% load and extra-long time (several years). However, creep property could be highly significant for applications such as mooring cables and bridge tension tendons where any slack from creep will have unintended consequences *(Burgoyne, 1992)*.

2.5. Resistance of Kevlar ® 49 to Chemicals and UV Light

Overall, Kevlar has an outstanding resistance to a wide range of chemicals and gases with the exception of strong acids and bases at elevated temperature and extended time (Kevlar Aramid® Fiber, 2013). This is by far the other key parameter which makes Kevlar a potential candidate. Unlike of steel, Kevlar has an exceptional resistance to most of the chemicals and gases found in most oil & gas wells. However, Sodium chloride with a concentration greater than 10% (at a temperature above 121^{o}C) and Ethylene glycol/water concentration in excess of 50/50% (at a temperature above 100^{0}C) are the only concerns identified (Kevlar Aramid® Fiber, 2013). Nevertheless, the design concept we are going to discuss in section three will address this concern through the use of plastic jacket as insulation.

However, the main weakness of Kevlar and most Aramid fibers is associated with their poor UV light resistance if used in unshielded environment. For example, exposure of Kevlar 1500Denier for 900 hours will make the fiber too lose its strength up to 75% which is highly significant and could make the material unsuitable for outdoor service (Kevlar Aramid® Fiber, 2013). However, by using insulation materials such as ETFE, we could easily shield Kevlar fiber from UV radiation. Moisture absorption is reported not to have any impact on the tensile strength of Kevlar fibers and not considered as main point of concern according to the most prominent scientist in the area, Burgoyne (1993).

2.6. The Science of Rope Construction (High Strength Synthetic Fiber Ropes)

Changing extra strong synthetic fibers into a high strength rope is proved to be the main challenge as the fiber - rope efficiency is affected by several factors. Despite the high strength of synthetic fibers (in excess of 3600 Mpa), the achievable efficiency for bigger cables is not much more than 55% of this value (Flory et.al, 1990). As the rope diameter increases, the net volume of the fiber or the compaction factor diminishes and the effective tensile strength achieved on the cross-sectional area will not be far from 2000Mpa as shown in figure 2.12. Kevlar and other high strength synthetic ropes comprise of several thousands of filaments being bundled as yarns and which in turn will be twisted to make strands and finally a rope of desired size as shown in figure 2.10.

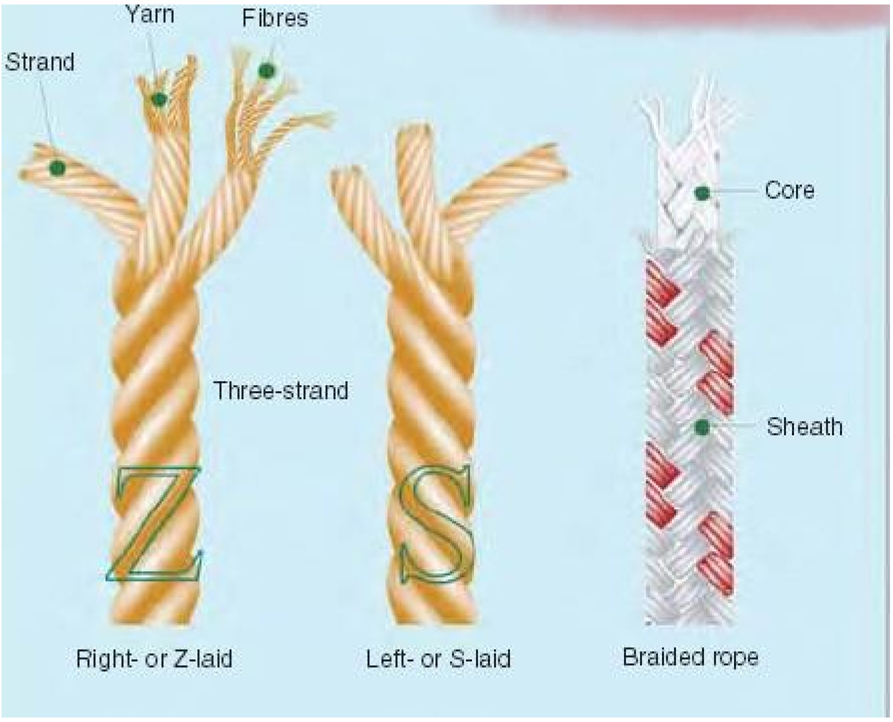


Figure 2.10: *Components of a typical synthetic rope (General Cargo Ship, 2010)*

In general, current practices of high strength composite cables could be viewed in three different groups depending on the arrangement of filaments, yarn, and/or strands within the cable.

- **Parallel Lay**

Cable and Rope construction parameters such as lay length, lay angle, and also the arrangement of Kevlar yarns and/or steel wires will have a direct impact on the strength of the final cable. Some claim that, Kevlar ropes based on parallel lay will have the maximum fiber - rope efficiency since the individual filaments are aligned parallel to the axis of the rope (Flory et al., 1990). This is true that, the loss in strength from filament to rope is associated with the twisting path the filaments follow as they wrapped from filament to yarn - to strand – to sub-rope and finally to a rope of considerable outer diameter and also further dealt by the research of Flory et al.(1990).

Some literatures explain this poor correlation between the strength of individual yarns and the output rope strength through the “bundle theory”, which states the relation between rope size and achievable strength. As we could see from figure 2.12, the curve makes asymptote at a value of 1930 N/mm^2 as the diameter of the rope gets larger and larger. However, we have to notice that, this is only the case of Kevlar® 29 and the value for Kevlar® 49 will deviate from this though the trend is more or less similar.

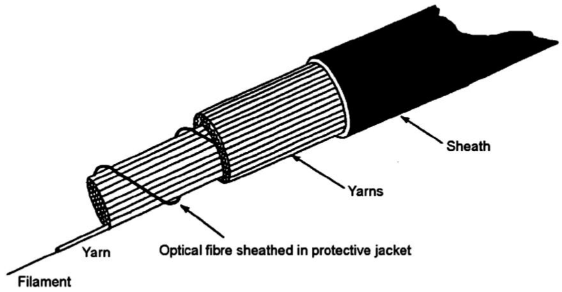


Figure 2.11: *Parallel lay fiber rope (Rebel et al., 2005)*

In general, though laying the fibers in parallel with the rope axis maximizes the rope efficiency in theoretical terms; it is highly dependent on the uniformity in strength, stress-stress, and other critical parameters of the individual yarns in the rope as explicitly discussed by Flory et al. (1990). The problem of parallel lay is that, damage or breakage of a single fiber will result in loss of strength in that fiber for a considerable length of the rope and it requires a larger length to obtain the necessary frictional strength to start carrying a load once again. In this type of lay, ensuring manufacturing uniformity and also uniform loading of all the fibers will be critical.Moreover, parallel lay will not be a possible option in the construction of monoconductor cables since the copper core could easily shift its position from the center to sideways during bending of the cable on drums. As a result, this type of cable construction is only suitable for mechanical cables without a copper core.

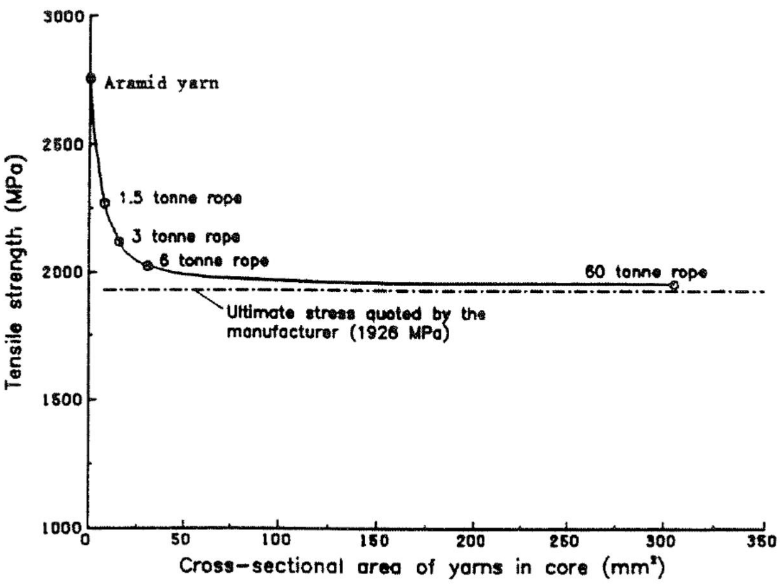


Figure 2.12: *Strength of the rope as a function of rope size based on Kevlar ® 29 fiber* (Flory et al., 1990)

- **Twisted Lay**

As we discussed earlier, parallel lay give us the highest fiber - rope efficiency, however, such type of rope construction requires a higher level of uniformity in the entire fiber in the rope and also its feasibility for cables with a core element inside is less viable. As a result, slightly twisting the yarn over a core element will enable us to minimize the characteristic length of the individual fibers needed to engage back if broken and also to avoid the sway of the core over the outer insulation.

Figure 2.13: *Twisted type rope (*Koordenfabriek, 2014)

As we could see from figure 2.13, the yarn will be made into strands which will further bundled over a core material. By maximizing the lay length (length of the rope per turn) , the impact of twisting the yarn on the tensile strength could be minimized and at the same time, the characteristic length required for broken filaments and any slight variation of the filaments could be easily accommodated.

- **Braided Lay**

In this type of construction, the fiber is bundled into yarn and in turn will be braided to make the rope as shown in figure 2.14. A rope constructed in this way possesses a limited stretch capability compared to twisted ropes though this property could also be desirable for ultra-long cables. In general, the overall breaking strength of this type of cables is limited as the fiber - rope efficiency is too poor. As a result, its application is largely limited to areas where stiff rope with a compromised strength is required.

Figure 2.14: *Braided rope type (*Koordenfabriek, 2014)

In summary, Parallel lay is considered to be the most efficient of all if fiber variability could be controlled and a low stretch coefficient rope is demanded. Twisted ropes are claimed to give a better fiber efficiency and excellent stretch coefficient while braided lay are proved to have a poor stretch coefficient and low fiber efficiency.

2.7. Definition of main Cable Design Parameters

Lay length and lay angle are two of the key design parameters with a greater impact on the strength, stretchability, torsion property, fatigue life, and other characteristics of the cable (Fatzer Service, 2001). Lay length refers the length of a pitch for one complete helical cycle of a wire, strand, or yarn. Where, the lay angle is the helix angle between the wire, strand, or the yarn and the cable/rope axis (FATZER service, 2001). Depending on the direction of the helix, cables and ropes could be designated as Right-Hand Lay (RHL) or Left-Hand Lay (LHL). However, most cables and ropes are constructed with two or more layers of strands in order to balance the rotational torque and couldn't be classified either RHL or LHL.

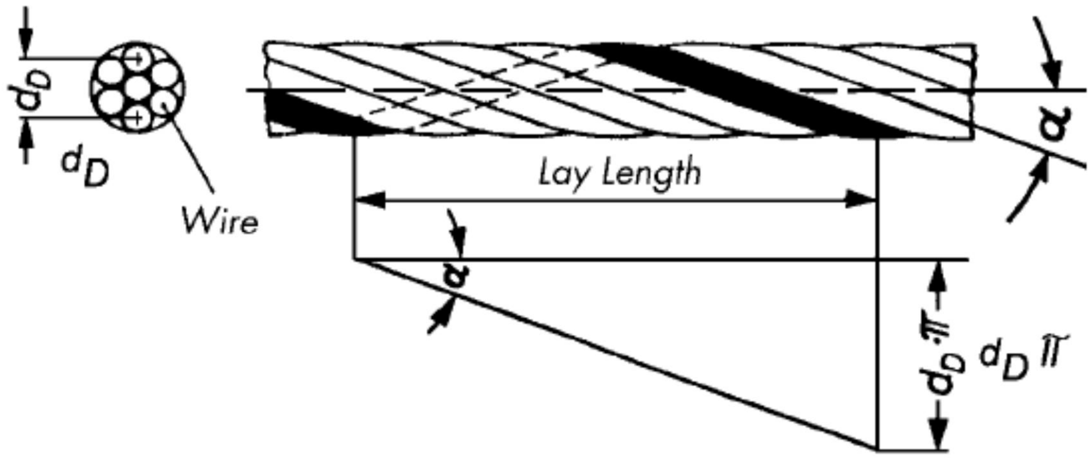


Figure 2.15: *Systematic description of lay length and lay angle* (Fatzer Service, 2001)

The relations between the mean diameters of the strands (d_D), the lay length (l), and the lay angle is as shown below.

$$\alpha = \arctan\left(\frac{\pi d_D}{l}\right)$$

Where

α - lay angle

d_D - pitch diameter of the helix

l - lay length

The value of l (lay length) is largely dependent on the pitch diameter with the function of (l/d) in the order of 6, 8, or 10 (Gibson, 2001). For the same cable diameter, a relatively large stretch coefficient could be achieved by using small l/d ratio. However, for specially tailored cables, the selection of this ratio will depend on the stretchability of all the other elements of the cable, namely the Kevlar strands and the copper conductors so as the intended load distribution and integration could be achieved within the working range of the cable.

In the terminology of rope design, lay length and lay angle are often described as the number of turns per inch of the rope. The optimal number of twists for Kevlar is in the order of 100turns per m as could been seen from figure 2.16. Here, the disagreement we could see between the theoretical and the experimental values is explained from the characteristic length of the filaments in the yarn and load transfer efficiency from filament to yarn as we discussed in section 2.6.1.

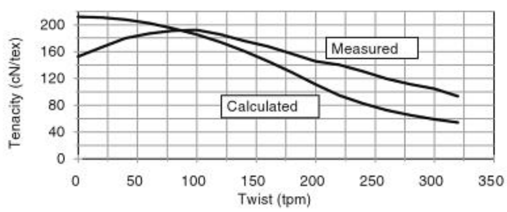


Figure 2.16: *Change of Strength of 1670 dtex aramid yarn with twist (Tsai, 1979)*

Theoretically, parallel lay gives the maximum strength at 0 tpm since the load transfer from the individual fiber elements to the yarn is the highest. However, experimental results (measured) values show that, twisting generates enough frictional force to arrest broken filaments from running loose to a considerable length and the strength of the cable reaches maximum at 100tpm as seen from figure 2.16. However, the above recommended value is only relevant to few strands of Kevlar yarns which bundles each other. The recommended parameter for Kevlar strands twisting over a relatively large diameter cable is expressed in terms of the twisting angle of the surface fibers over the core element with a typical value of 7^0 as expressed in the same rope handbook.

3. CONCEPT DEVELOPMENT & THEORETICAL ANALYSIS

3.1. Introduction to the New Design Approach

As stated in section 1.2, the current cables are characterized by limited strength, relatively heavy weight, poor H_2S resistance (regular steel cables), too expensive (corrosion resistance cables), and other operational related problems. Moreover, the potential to improve the currently used steel based Monoconductor cables seem too difficult (if not impossible) as cable manufacturers optimize the design for several years and reach the material limit. However, research outputs from different scholars and organizations indicate the possibility of substituting steel based cables and ropes with high strength fibers and some have already expressed their success story in replacing steel based mechanical cables with high strength synthetic fiber ropes as we discussed in section 2.1.

As a result, I have come up with the idea of replacing the steel armors in Monoconductor cables with high strength synthetic fibers (Kevlar® 49) and in line with current research and development directions. The main argument behind this proposed change exists in improving the specific strength of the cable at large and other issues as secondary goals. However, a 100% shift from steel based cables to synthetic fiber based cables come up with its own complications as the steel armor in the current cables is used not only as load carrying and protective armor but also as a current return path. As a result, finding a new and tailored design approach which exploits the novel property of Kevlar® 49 fiber without compromising other parameters of the cable is the main focus of this work.

3.2. Alternative Design Concepts Investigated

As oil & gas wells become deep and also deviated, the strength of the cable is often consumed with its weight and this in turn leave a limited operational strength for the actual job. Moreover the problem could be even worse if the well contains H_2S and other gases as its forces the use of corrosion resistance cables and known to have even a lower braking strength. As a result, our main focus will be in replacing the steel armor with Kevlar® 49 fiber so as to improve the cable performance without making any change on the overall diameter of the cable.

However, Kevlar's relative weak abrasion and wear resistance behavior combined with the need to have a conducting material for the returning current make the idea of changing the entire steel armor with Kevlar fibers unrealistic. To overcome this, the design approach has focused in creating a composite electromechanical cable which is lighter, stronger, and at the same time satisfies all other operational requirements. After investigating the different possibilities of incorporating Kevlar®49 fiber and steel armor in a 5/16" monoconductor cable, 3 alternative approaches (here after referred as design concepts) are generated and further investigated based on their respective potential towards improving the limitations of the currently used cables.

A. Design Concept - I

In this design concept, the diameter of the inner armor wires in the current 5/16" cables changed from 1.13mm to 0.617mm and also a significant portion of the plastic insulation material (1.714 mm thickness) is reduced so as an annulus area shown in figure 3.1 could be achieved. Since Kevlar ® 49 fiber is lighter, stronger, and cut resistance, the new composite cable was initially expected to have an enhanced property with the minimal change incorporated. However, preliminary results show that, the weight reduction is limited to 8% and also the overall technical feasibility of the concept to address the limitation of the current cables is found insignificant. As a result, the concept is found to be less feasible and dropped out from further investigation.

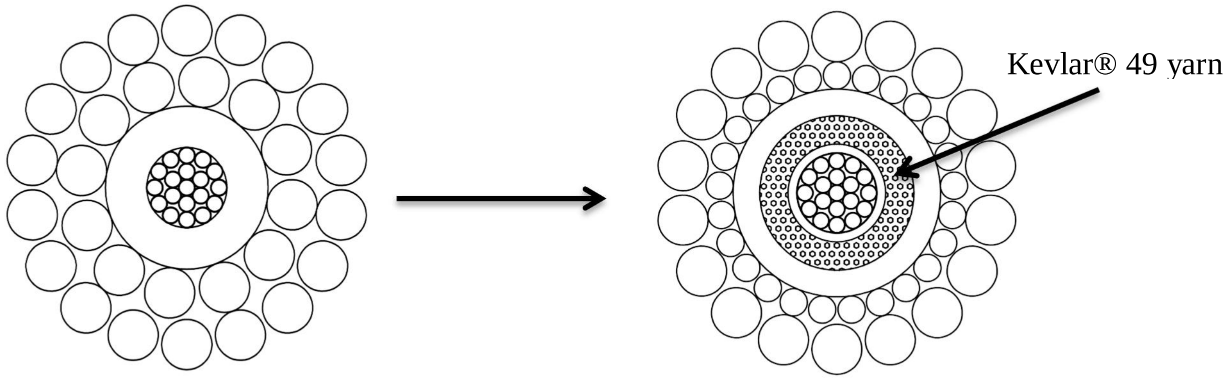


Figure 3.1: *Cross sectional view of the concept under discussion© Yohannes / UiS /AI*

B. Design Concept - II

What makes this design approach different from concept I is that, not only the inner armor wires, but also the outer armor wires are changed from 1.13mm to 0.787mm diameter which are among the commonly used standard wire diameters.

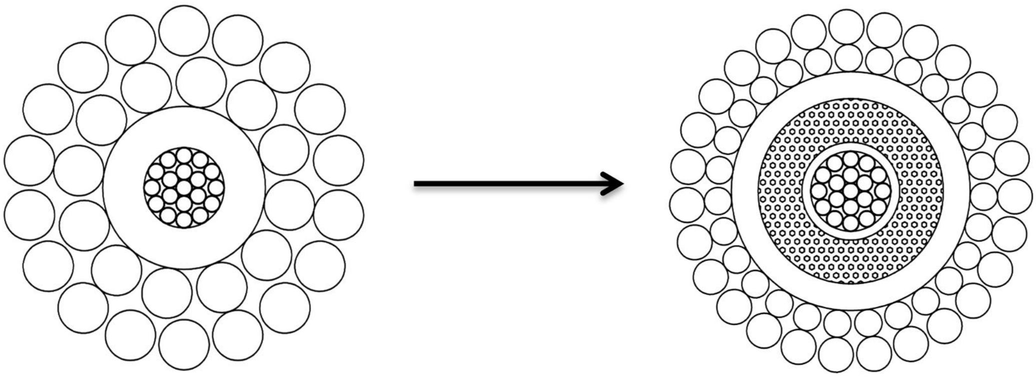


Figure 3.2: *Cross sectional view of the concept under discussion© Yohannes / UiS /AI*

However, reducing the armor wires from the current 1.13mm wires to 0.787mm and 0.617mm is found to increase the electrical resistance of the armor wires. The increment is found significant if the armor wires are made of stainless steel as it possesses a relatively higher electrical resistance compared to regular steel. However, this unintended problem could be solved by using conductive tapes in between the armor wires and the insulation material so as the electrical resistance of the armor could be reduced significantly. The concept is currently practiced by cable manufacturers such as Camesa (7H42 multi-conductor) and could be adapted to our new design approach as well.

Table 3.1: *Geometrical description of the cable - Design concept II*

Description	Value	Unit
• Cable Diameter (outer diameter)	8.18	mm
• Diameter and Number of Armor Wires		
▪ Outer Armor	27 x 0.787	mm
▪ Inner Armor	27 x 0.617	mm
• Diameter of the copper conductor core		
▪ Copper wires in the core (dia. 1.804)	1.804	mm
▪ Diameter of individual wires	19 x 0.361	mm
• Insulation		
▪ Outer jacket thickness	0.60*	mm
▪ Inner insulation/tape thickness	0.2	mm
• Epoxy Impregnated Kevlar thickness	0.98	mm

** Net geometrical thickness (not manufacturing thickness), see section 3.3.1*

C. Design Concept III

In this design approach, instead of using two layers of armor wires, we use only one outer layer as abrasion resistance, return path for the current, and also to carry a portion of the tensile load. By doing so, it will be possible to get more annulus area for the Kevlar®49 fiber and also significant reduction in weight.

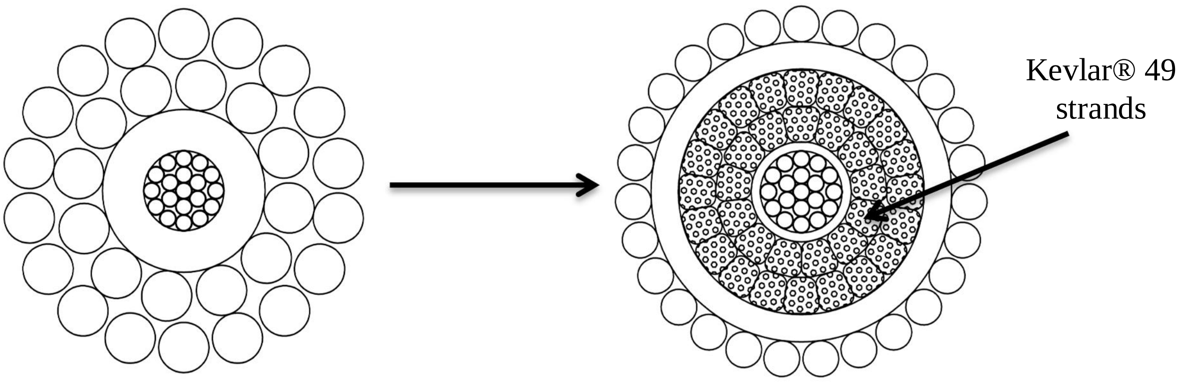


Figure 3.3: *Cross sectional view of the concept under discussion© Yohannes / UiS /AI*

Typical wire sizes initially considered was 1.13mm (18wires), 0.787mm (27wires), and 0.617(34 wires) which are all standard wire diameter sizes and currently in use. Reducing the wire size has a positive effect in shrinking the cable weight, improving the breaking strength, fatigue life, grease consumption, and the tendency of gas breakthrough at the grease stuffing box, and other operational benefits. However, decreasing the armor wires excessively also increases the electrical resistance of the armor beyond tolerable limit.

Moreover, small frictional and aberrational wear damage, material and manufacturing related defects, and also the large number of wires to deal with poses its own challenge as we excessively reduce the armor wire diameter. After investigating the pros and the cons, the size of the armor wire is set to be 0.787mm though this armor size could be changed at the lateral stage of the project either in consultation with manufacturers or based on test results on prototype cables.

Table 3.2: *Geometrical Description of the cable- Design concept III*

Description	Value	Unit
• Cable Outer Diameter	8.18	mm
• Diameter and number of Armor Wires		
▪ Outer armor	27 x 0.787	mm
• Insulation		
▪ Outer insulation thickness	0.6	mm
▪ Inner insulation thickness	0.20	mm
• Epoxy Impregnated Kevlar thickness	1.60	mm

As seen from table 3.2, a thickness of 1.6 mm could be retrieved and made available to incorporate the Kevlar fiber and which in turn enable us to reduce the weight of the cable up to 31 % in air (or 37% in water) and also a considerable increase in the breaking strength of the cable (please see section 3.3.3 and 3.3.4 for details).

3.3. Detail Design Analysis of Selected Concepts

In section 3.2, we have generated 3 alternative design concepts and picked two of the concepts (***Design concept II and III***) worthy enough for further investigation. However, before we proceed further, let us we discuss some of the key design variables which are believed to have a significant impact on the breaking strength and weight of the cable under discussion.

3.3.1. Key Design Variables

The expected breaking strength of the cables under discussion are affected by the type of the armor material used, the efficiency of the manufacturing process in harvesting the high strength Kevlar® 49 yarn, and the thickness of the outer insulation material (jacket).

- **Strength of the Steel Armor Wires**

Based on current practices of cable manufacturing, steel armors are made of two category of materials, high strength steel or stainless steel depending on the corrosive nature of the oil & gas wells to operate. Rather than picking values from general material property tables, I have preferred to use the rated breaking strength of currently used cables and calculate respective ultimate strength of the two categories of materials (high strength regular steel and corrosion resistance steel) as follows.

Table 3.3: *Breaking strength of typical 5/16" CAMESA Monoconductor cables (*Camesa, 2013*)*

Cable Type	1 N 32	1 N 32 S77
• Cable Breaking Strength	53.3 KN	45.4 KN
• Average Wire Breaking Strength ▪ Outer Armor (18 x 1.13mm) ▪ Inner Armor (12 x 1.13mm)	 1.97 KN 1.97 KN	 1.66 KN 1.66 KN

Comparing the breaking strength of these two categories of cables and the capacity of the armor wires, we will find the presence of efficiency gap between the total carrying capacity of the individual wires and the breaking strength of the cable. The efficiency is calculated and found to be in the order of 90.2 % for high strength cables and 91.16 % for the corrosion resistance cables.

Based on the above argument, we could easily calculate the ultimate tensile strength of the currently used armor wires by simply dividing the rated breaking strength of the cable to the total cross sectional area of the armor wires or dividing the breaking strength of the individual armor wires and multiplying this with the percent efficiency we found earlier.

$$\sigma_U = F_B / A$$

Where:

F_B - Breaking strength of the armor wires

A - Cross sectional area of a single armor wire and,

σ_U - Ultimate tensile strength of the armor wire

From this, we could summarize that, the ultimate strength of the two categories of armor wires to be in the order of 1964MPa for the high strength and 1655Mpa for the corrosion resistance versions respectively.

- **Achievable Strength of Kevlar® 49 Strands**

As it is known, the strength of Kevalr®49 fiber (up to 3600Mpa) is almost double the strength of steel though the practically achievable value is quite lower than the strength of the individual fibers. Based on our discussion on the literature part (section 2.6), the practically achievable strength of Kevlar based ropes to be in the range of 1926Mpa (large diameter ropes) - 2750 Mpa (smaller diameter ropes).

The main reason for loss of strength as the diameter of the rope increases is associated with the loss of fiber compaction factor or volume percent of the fiber in the cross sectional area. However, the presence of a lateral squeezing force from the outer steel armor wires and size of the cable we are discussing are found to be in favor of the above argument. As a result, Kevlar® 49 strand strength of 2250Mpa is considered to be reasonable and easily achievable though a much higher strength could also be considered depending on the quality of the fiber and the efficiency of the entire manufacturing process.

- **Thickness of the Outer Insulation Jacket**

The third important point and worthy to discuss is the practical thickness of the outer insulation jacket. As the jacket shares the useful cross sectional area of the Kevlar®49 fiber, it is our objective to make the size of this insulation material as minimum as possible. However, practical issues such as manufacturability and puncture from the squeezing effect of the armor wires pose a typical threat. For this reason, a jacket thickness of 0.6 + 2/3 (the diameter of the armor wires) during construction or a compressed and net geometrical diameter of 0.6mm is found practically feasible and proportional to the size of the armor wire(details in section 3.3.8). Moreover, the presence of the Kevlar®49 fiber in between the armor wires and the copper conductor will give us extra confidence when comes to the danger of short circuiting related problem and known to be a common problem of currently used monoconductor cables.

Table 3.4: *Summary of Key Design Variables with some degree of uncertainty*

Description	Value(s)	Unit
• Insulation Thickness(effective)		
▪ Outer Insulation jacket	0.6	mm
▪ Inner Insulation tape	0.2	mm
• Strength of the armor (90 %)		
▪ Regular steel based	1768	Mpa
▪ Stainless Steel based	1490	Mpa
• Achievable Strength of Kevlar ®49 strands (62.5 %)	2250	Mpa

In general, the cables we are going to design are expected to have a wider variation both in strength and weight. However, the deviation between the high strength and corrosion resistance cables is found to be quite significant and the two categories of cables will be dealt separately unless and otherwise stated differently.

3.3.2. Lay Length and 3D Model of the Cables under Investigation

As discussed in section 2.6, the lay length is the main geometrical parameter in the design of ropes and cables as it governs the stretch coefficient, rotational stability, fatigue life, and other important aspects of the cable. Thus, finding the optimum lay length of the steel armor wires and the Kevlar fiber strands is a main issue of interest. Literatures referred recommended a ratio of lay length (l_A) to pitch diameter (d_{DA}) of steel based wires in the order of 6, 8, or 10 (Gibson, 2009). For example, the lay length of the currently used CAMESA 5/16’’ cables is also measured and found to be 65mm or l_A/d_{DA} ratio of 9.22 and consistent with recommended values. Based on this knowledge, the optimum lay length of the two cables discussed on the two different design concepts will be as follows.

- **Design Concept II**

As the annulus area of the Kevlar fiber in this design concept is limited to 0.98mm, the Kevlar yarn could be twisted over the copper core without forming Kevlar strands. This in turn minimizes the difference in stretch coefficient between the Kevlar®49 fiber and the steel armors wires. As discussed in the literature review and also indicated in section 3.3.6 in detail, the relatively large stretch coefficient of the Kevlar fiber could only be balanced by giving the steel armors wires more constructional stretch capacity. Practically this could be achieved by adjusting the l_A / d_{DA} ratio. As a result, a lay length - to - pitch diameter of 8 could be taken at this stage and re-calibrated latter if the stretch coefficient of the steel armor wires and the Kevlar fibers deviates substantially.

Description	**Wire diameter, d_A**	**Pitch diameter, d_{DA}**	l_A / d_{DA}	**Lay length, l_A**
Outer armor	0.787 mm	7.393 mm	8	59 mm
Inner armor	0.617 mm	5.989 mm	8	48 mm

In the same manner, the lay length (or number of twists per meter for the Kevlar fiber) could also be determined as follows.

Mean Kevlar pitch diameter, d_{Dk} = Diameter of the core + ½(2x thickness of the annulus area)
= 2.204 + 0.980 mm
= 3.188 mm

The optimum twisting angle for Kevlar®49 fiber is conducted by scholars and reported to be around 7^0 *(Tsai, 1979)*.Based on this information, the angle of twist and the optimum lay length for Kevlar fibers could be calculated as follows.

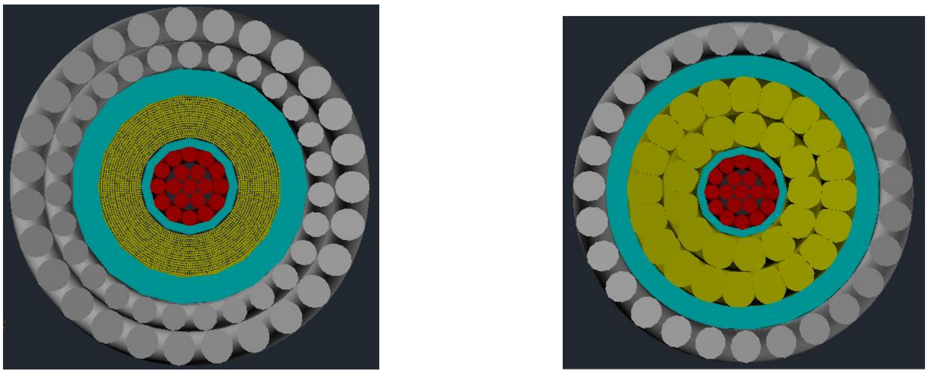
$$\text{Lay Length} = \pi\, d_{Dk} / \tan \alpha \approx 82 \text{ mm}$$

- **Design Concept III**

The steel armor in this design concept has only a single layer and as a result, there exists a relatively large annulus area for the Kevlar fiber. For this reason, the fiber will be laid in strands so as the cable will not deform at the sheaves and this sequentially will result extra stretchability of the Kevlar fibers. To compensate this, a relatively smaller l_A/d_{DA} (6) is taken at this stage and will also be verified in section 3.3.6 for its conformance.

Description	**Wire diameter, d_A**	**Pitch diameter, d_{DA}**	**l_A / d_{DA}**	**Lay length, l_A**
Outer armor	0.787 mm	7.393 mm	6	44 mm

In this design concept, the annulus area available for the Kevlar fiber is found to be 1.601 mm and wider than the one discussed earlier. In order to maximize the fiber - rope efficiency, and also balance the rotational stability of the cable, it is found better to lay the Kevlar fiber in strands of two layers and as seen in figure 3.4 (b).



a. Design concept II change b. Design Concept III

Figure 3.4: Arrangement of the *Kevlar®49 yarns/strands in the two design concepts ©Yohannes/ UiS /AI*

In general, the number of Kevlar ®49 strands (n_s), strand diameter (d_s), and the average pitch diameter (d_{DK}) in each layer could be either calculated from the circumference or determined from the geometry and found to be 13 strands in the inner layer and 20 strands in the outer layer. Moreover, the summary of the lay length and the pitch diameter of the two cables discussed under design concept II and III are summarized as shown table 3.5.

Table 3.5: *Summary of optimum lay length and strand sizes*

Design Concept	Kevlar Strands				Armor Wires			
	n_s	d_s , mm	d_{Dk} , mm	l_k, mm	n_A	d_A, mm	d_{DA}, mm	l_A , mm
II	-	0.980	3.188	82	27	0.617	5.989	48
					27	0.787	7.393	59
III	13	0.801	3.005	77	27	0.787	7.393	44
	20	0.801	4.606	118				

The 3D model is found to be consistent with the theoretical number of the armor wires set in each design concepts at the beginning with an allowance of 0.04mm between each adjacent armor wires so as the cable could initially stretch from the construction allowance. In general, the two cables discussed under design concept II and III will look like the ones shown in figure 3.5 and 3.6 which are generated by using AutoCAD 3D modeling software.

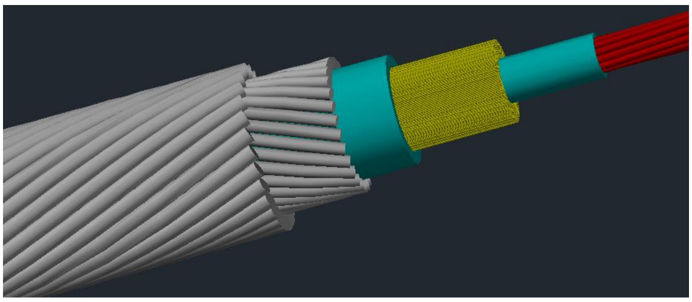


Figure 3.5: *3D View of the Cable (Design Concept II) ©Yohannes/ UiS /AI*

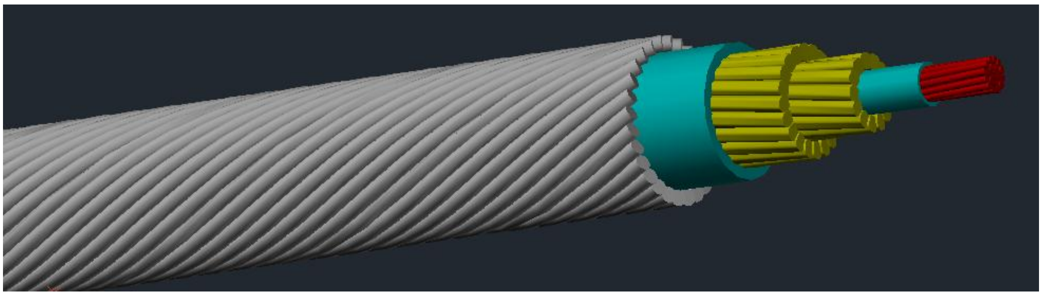


Figure 3.6: *3D View of the Cable (Design Concept III) ©Yohannes/ UiS /AI*

3.3.3. Theoretical Breaking Strength of the Cable

As the tensile strength of stainless the steel armor is quite different from that of regular steel armor, our discussion on the cable strength will deal with a total of 4 cables, two cables for each design concept. Achievable armor strength of 1490Mpa for stainless steel armor and 1768 for high strength regular steel armor, and 2250Mpa strength for the Kevlar fiber will be utilized based on discussion in section 3.3.1. Having these values in mind, the breaking strength of the cables under the two design concepts could be calculated as follows.

Note that, the theoretical breaking strength of the cable (S_B) is the sum of the breaking strength of the Kevlar fiber (S_K) and breaking strength of the armor wires (S_A) on assumption that, the difference in elongation between the steel armor and the Kevlar fiber will be fully addressed.

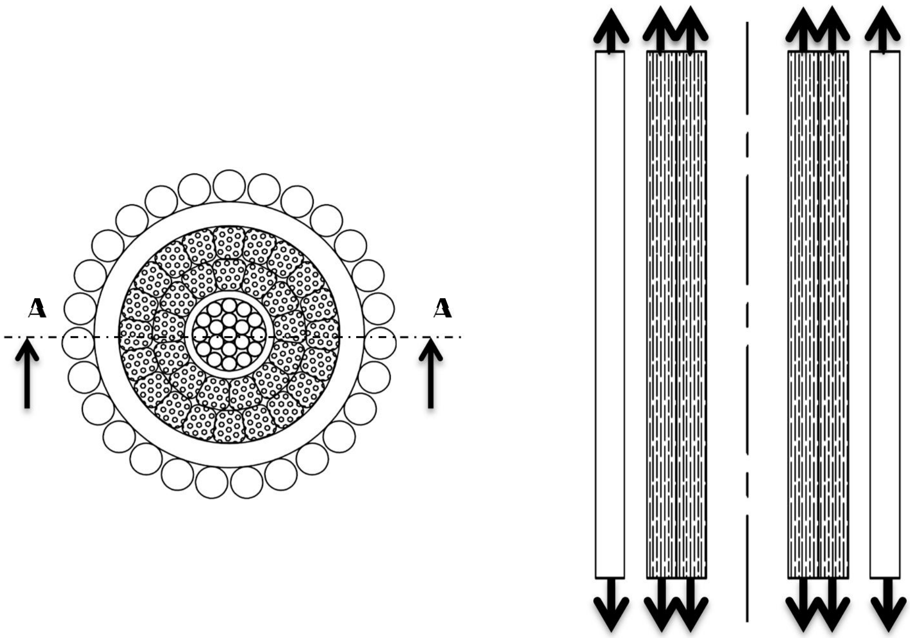


Figure 3.7: *Load distribution under tensile load – Section A-A©Yohannes/ UiS /AI*

$$\Rightarrow S_B = S_A + S_K$$
$$= \sigma_A . A_A + \sigma_K . A_k$$

Where

σ_A - Strength of the armor wires

A_A - Total cross sectional area of armor wires

σ_K - Strength of the Kevlar®49 yarn

A_K - Annulus area of the Kevlar fiber

Using the above equation and the numerical values we agreed earlier, the theoretical breaking strength of the cable under the two design concepts will be as seen in table 3.6.

Table 3.6: *Summary of the theoretical breaking strength of the cable*

Design Concept	Theoretical Breaking Strength (KN)
Design Concept II	
• High Strength Steel Armor	59.8
• Stainless Steel Armor	54.2
Design Concept III	
• High Strength Steel Armor	66.3
• Stainless Steel Armor	62.9

As it is known, the breaking strength of a cable is best determined through laboratory experiments and taking the average value of the samples tested. As a result, the values estimated here could only be used as an insight and not as a true value as it could have a significant deviation though ultimate care is taken not to include unachievable values.

3.3.4. Theoretical Weight of the Cable

In practice, the weight of the cable is associated with the density of the materials found in the cable and the net volume of these materials per unit length of the cable. Though it is complicated and difficult to calculate the exact weight of the cable, a good approximation could be done with a smaller margin of error or uncertainty. Below is the summary of the different materials utilized in the construction of the concept cables and their respective density.

Table 3.7: *density of materials utilized in the design process*

Description of the Material	Density (kg/m3)
Steel Armor	7860
Kevlar Fiber	1440
Copper Conductor	8940
Outer Insulation-ETEF	1700
Inner Insulation – Tape	1700
Electrical conducting tape (Ni-Cu)	8920

In order to determine the total weight of the cable, it is necessary to determine the volume of the different materials within the cable. To simply things, the volume occupied by the Kevlar fiber, the insulation layer, and inner binding tape and the conducting tape are considered as cylindrical annulus volume. However, the weight of the armor and the copper wires is calculated taking in to account their diameter, numbers of wires, and the actual length of the wires per km of the cable.

In design concept II, we have 27 outer armor wires and 27 inner armor wires with a diameter of 0.787mm and 0.617 mm respectively. Since the actual length of the wires is different from the total length of the cable, we have to use the lay length to calculate the actual length of the individual wires. The relation between lay length, pitch diameter and the actual length of the wires in the cable is given as follows.

Actual Length of the wire per lay length, $L_{Actual} = \sqrt{((\pi\ d_{DA})^2 + l_A^{\ 2})}$

$\Rightarrow L_{actual} = 51.56$ mm/48mm for the inner armor and,

$\Rightarrow L_{actual} = 63.41$ mm/59mm for the outer armor,

The above values are equivalent to 1.074 km per km of the cable in consideration and found to be slightly longer than the length of the cable in consideration (1km). Once we determine the actual length of the individual armor wires, calculating the weight is as simple as calculating the weight of a wire with known diameter and length. In the same manner, the weight of the Kevlar fiber within the cable could also be estimated as follows:

- Outer diameter of the Kevlar Annulus, 4.172mm
- Inner diameter of the Kevlar Annulus , 2.204 mm

This give us an annulus area of 9.86mm^2 based on 100 % space utilization of Kevlar fiber though there exists up to 15% unutilized space in between the individual fibers. Following the same procedure, we will find the weight of the different components utilized in design concept II as follows.

Table 3.8: *Theoretical weight of the cable in kg/km for design concept II*

Description of Cable Component	**Values (kg/km)**	
	Regular Steel armor	**Stainless Steel Armor**
Unit weight of the armor part	179.26	179.26*
Unit of the Kevlar Fiber	15.26	15.26
Unit of weight of the copper wires	18.59	18.59
Unit weight of the outer insulation	20.93	18.12
Unit weight of the inner tape	2.93	2.93
Unit weight of the conducting tape	-	14.77**
Theoretical Unit Weight of the Cable	**242.5**	**254.4**

** Small density difference between regular steel and stainless steel is neglected*

*** Conducting tape is used to reduce electrical resistance of stainless steel armors (see section 3.3.5)*

Based on the above approach, the weight of the cable under the two different design concepts could be summarized as shown in table 3.9. Moreover, the weight of the cable in water could also be calculated based on the Archimedes principle.

Table 3.9: *Theoretical weight of the 4 cables designed under the two design concepts*

Description	Concept II		Concept III	
	Regular Steel	Stainless Steel	Regular Steel	Stainless Steel
Weight in Air (kg/km)	242.46	254.41	203.78	219.31
Weight in Water (kg/km)	191.46	203.41	152.78	168.31

Note that, the approach used to calculate the weight of the cable is also used to calculate the weight of the currently available cables so as to make a crosscheck on its validity and found to be consistent with an error margin of only 1.86 % or a difference of 5.48kg/km and this value is added in all calculations simply as a calibration constant.

3.3.5. Electrical Resistance of Armor Wires

Mono-conductor cables convey electricity via the copper conductors located at the core of the cable and armor wires as current return paths. The main problems found are related to short circuiting from tear of the insulation layer and also from buckling of the copper conductors as a result of excessive elongation and failure to spring back with the steel armor. Except addressing these two problems, any attenuation of the electrical property of the cable is not found necessary.

The universal formula for electrical resistance of a wire says that, resistance is directly proportional to length and inversely proportional to the cross-section area of a wire with resistivity as a constant of proportionality.

$$\Rightarrow \quad R = \rho\, l/A$$

Where

R = Resistance of the cable, Ω/m

ρ = material resistivity, Ω.m

l = Length of the cable, m

A = Total cross sectional area of the armor wires, m^2

Typical mono-conductor cables currently in use have a typical armor resistance of 6.9 Ω / km (regular steel armor of type 1N32) or 36.7 Ω /km (stainless steel armor of type 1N32 S77). This is equivalent to a material resistivity of 2.08×10^{-7} Ω .m and 1.11×10^{-6} Ω .m for regular steel and stainless steel armor respectively. Having these resistivity values for the two armor material categories, the electrical resistance of the armor in the new design concepts could be easily calculated. For example, in design concept II, we have two layers of armor wires with a total cross sectional area of 21.22 mm^2. Taking a 1000m length of the cable and the parallel circuit theorem to add the electrical resistance of the individual armor wires which could be assumed to be parallel, we could calculate the electrical resistance of the cable as follows.

Case 1- If the armor material is made of high strength steel, $\rho = 2.08 \times 10^{-7}\ \Omega.m$

$$R = \rho\, l / A$$

$$R = 2.08 \times 10^{-7}\ \Omega.m \times 1000\ m / (21.22 \times 10^{-6}\ m^2)$$

$$= 9.79\ \Omega/km$$

Case 2- If the armor material is made of Stainless steel, $\rho = 1.11 \times 10^{-6}\ \Omega.m$

$$R = 52.35 \Omega/km$$

From case 1 and case 2, we could conclude that, the electrical resistance of the armor is within the acceptable range if the armor is made of regular steel. However, the use of conductive tapes as reinforcement is mandatory if the armor is made of stainless steel so as the electrical resistance could be kept as low as possible (the highest operational resistance currently in practice is limited to 36.7 Ω/km , 5/16″ stainless steel cable, e.g. 1N32 S77).

In general, the use of conducting tapes to improve the electrical property of cables is not a new idea and quite dozens of products are already available and the one shown in figure 3.8 could be a typical product which uses conducting tape to improve the electrical property of the cable. The main advantage of conductive tapes, foils and gaskets is that, they have a very thin cross section, light weight and efficient space utilization.

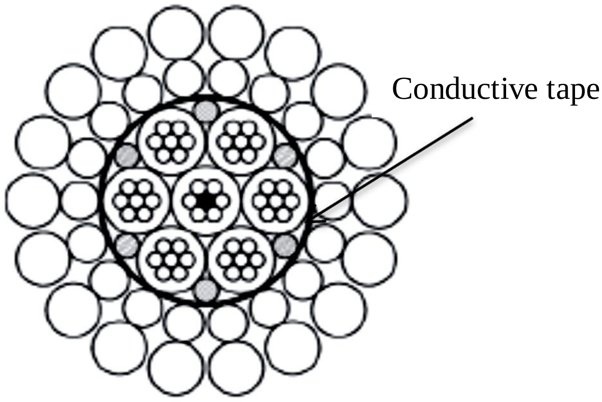


Figure 3.8: *Multiconductor cable with a conductive tape* (Camesa, 2013)

Conductive tapes, foils and gaskets are made of copper, copper - nickel, copper - tin, carbon, or even from silver and gold depending on the type of application. For our case, a conductive tape from companies such as Parker Hannifin Corporation (product ID – CCK) and 3M could be potential candidates as these tapes are rated as corrosion resistance and applicable up to 205 ^{0}C working temperature. Moreover, the current supplier (camesa) is also using such products in some of its well intervention cables and could be a major source of reliable information in the subject area if selected as a potential manufacturer of these concept cables.

Now taking, < 0.0005 Ω /cm ^{2} as the rated surface resistance of this materials and a net conductive material thickness of 0.0889 mm, the electrical resistance of the conductive tape could be calculated as follows.

$R = \rho \, l / A$

$\Rightarrow \quad = \rho \, l / (t. \, w)$, where t(thickness) and w(width)

$\Rightarrow \quad = Rs. \;\; l/w$ where Rs is surface resistance

Now taking the circumference of the cable as the width (2.075 cm and 1.688cm for DCII and DCIII respectively) and 1000m long cable, the resistance of the conductive tape will be as follows.

R= Rs. l /w

= 0.0005 Ω /cm ^{2} x 100,000 cm / (2.075cm or 1.688cm)

= 24.09 Ω/km for design concept II and 29.62Ω/km for design concept III

The total electrical resistance of the armor will be the sum of the resistance of the armor wires and the conducting tape and could easily be calculated based on the parallel circuit theorem.

$$R_{total} = \frac{R_{tape} \times R_{armor}}{R_{tape} + R_{armor}}$$

Table 3.10: *Summary of the theoretical electrical Resistivity of the armor*

Design Concept	Armor Resistance , Ω/km		
	Regular Steel	Stainless Steel Armor	
		Without Tape	With tape
Design Concept II	9.79	52.35**	18.92
Design Concept III	15.81	84.53**	18.75

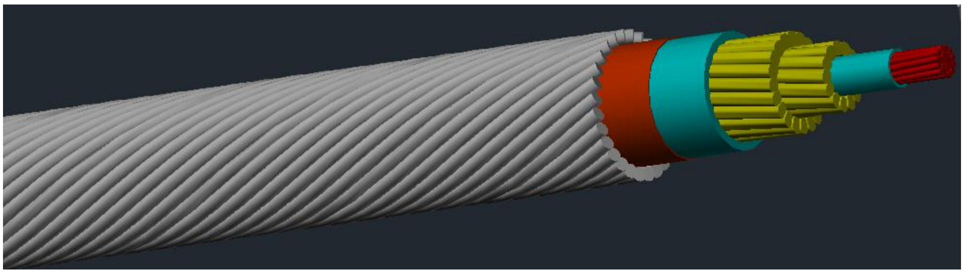


Figure 3.9: Stainless steel Armor with conducting tape ©*Yohannes/AI/UiS*

By the use of a conductive tape, the electrical armor resistance could be corrected to an acceptable value which is theoretically found to be 50% less than the currently used corrosion resistance cables. Despite the larger number of armor wires we have in design concept II , design concepts III has enabled us to have a more or less similar armor resistance as the conductive tape carries most of the return current and which is relatively larger for this design concept.

3.3.6. Stretch Coefficient of the Cable

The main challenge of this composite electro-mechanical cable is found to be the task of matching the strain stress behavior of the two load carrying elements, the kevlar®49 fiber and the steel armor wires. It is obvious that, failure to match the stretchability of the two units will lead to overstressing of the less stretching member and hence failure could happened at a much lower load level than normally anticipated. Though the stretch coefficient of the cable could be best determined from laboratory tests, a preliminary estimation could be made using recommended approaches from literatures and also relevant values from cable hand books.

As it is known, the stretch coefficient of a cable is composed of two unique components, the *constructional stretch* and *the elastic stretch* (Gibson, 1999). The constructional stretch is a function of the geometrical change of the cable due to an applied; the armor wires slide slightly and along the helical lay length depending on the looseness of the initial construction, the squeezability of the core materials, the pitch diameter of the cable, the lay length, and the age of the cable (new cables stretch more) (Gibson, 1999)Whereas, the elastic stretch of the cable is a mere result of the actual elongation of the individual wires under elastic strain and follows the same pattern as the strain - stress line.

In order to better understand the stretchability of the steel armor wires and the Kevlar ®49 fibers in the design concepts we are discussing, let us we take three representative elements of the cable and model them as seen in figure 3.10. From the figure, we can understand the analogues property between this model and a spring mechanism with two or more springs in parallel. For the same amount of force applied (F), the three springs will generate different resistance (force) and known to be proportional to their stiffness (K) since the amount of compression or elongation is going to be the same for both springs. Based on this knowledge, the kevlar®49 fibers and the steel armor wires could be modeled as springs just changing the spring stiffness by the material stiffness (or modulus of elasticity).

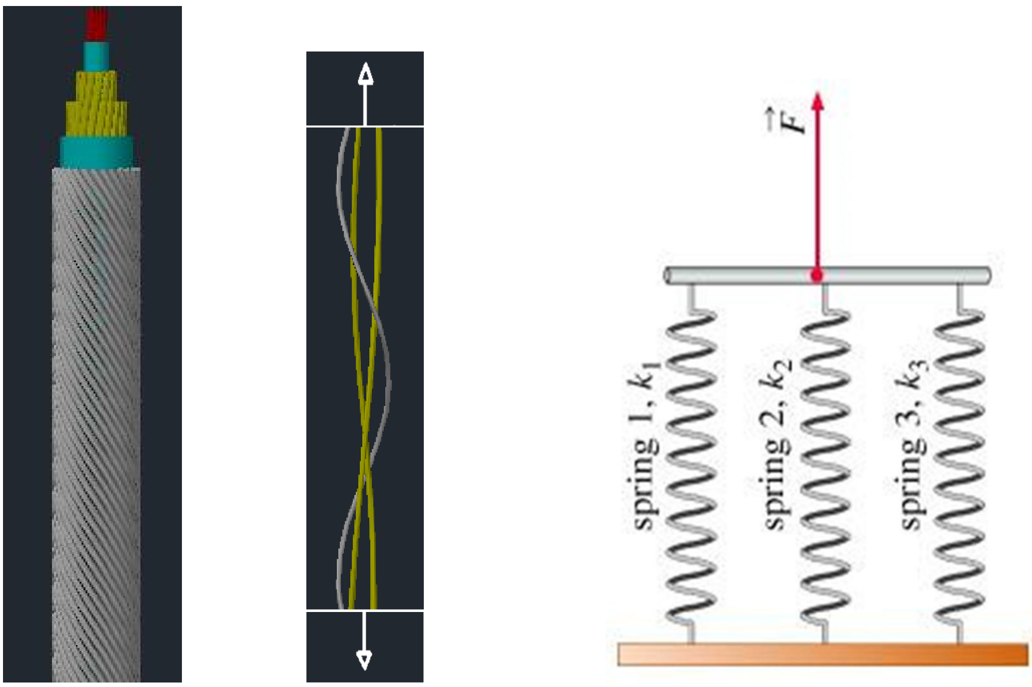


Figure 3.10: *Representative the load carrying members as springs in Parallel ©Yohannes/UiS/AI*

Based on this hypothesis, the stretch coefficient of the cable could be calculated using the same approach as we use for composite materials (fiber - matrix) as follows.

$$F_{Cable} = F_{armor} + F_{Kevlar}$$

$$\Rightarrow \quad \sigma_{Cable} \,.\, A_{Cable} = \sigma_{armor} \,.\, A_{armor} + \sigma_{Kevlar} .\, A_{Kevlar}$$

Where, σ_{Cable} is a hypothetical and imaginary uniform stress (equivalent) with the load bearing area of the cable (A_{Cable}) and considered to be the sum of the total armor cross sectional area and the Kevlar annulus area.

$$\Rightarrow \quad E_{Cable} .\, \varepsilon_{Cable} \,.\, A_{Cable} = E_{Armor} .\, \varepsilon_{Armor} \,.\, A_{Armor} + E_{Kevlar} .\, \varepsilon_{Kevalr} \,.\, A_{Kevlar}$$

$$\text{but} \quad \varepsilon_{Cable} = \varepsilon_{Armor} \approx \varepsilon_{Kevlar\,,\,elastic} = \Delta l/l$$

$$\Rightarrow \quad E_{Cable} .\, A_{Cable} = E_{Armor} .\, A_{Armor} + E_{Kevlar} .\, A_{Kevlar} \qquad \text{or}$$

$$\Rightarrow \quad E_{Cable} = E_{Armor} .\, \omega + E_{Kevlar} .\, (1-\omega), \quad \text{where } \omega = A_{Armor} / A_{Cable}$$

From the geometry of the cross-sectional area of the two design concepts under investigation, the value of ω is found to be 0.68 for design concept II and 0.41 for design concept III. Moreover, wire rope handbooks refer the modulus of elasticity of armor wires in steel cables to vary from 26% to 50% of the actual modulus of elasticity of the wire material and a typical value of 40 % is considered as best estimate for standard steel wires (*Heisler, 1998)*. Furthermore, the modulus of elasticity of high strength steel and stainless steel armor materials could be taken as 207 Gpa and 193 Gpa respectively (Youssef et al., 2011).In reality it is this values which makes product testing much more reliable than the theoretical values which we are going to generate here onwards though the values could serve as a good starting point.

$$\Rightarrow \quad E_{Armor} \approx 0.4 \text{ x } 207 \text{ Gpa}$$

$$\approx 82.8 \text{ Gpa for high steel or } 77.2 \text{ Gpa for stainless steel armor}$$

In the same manner, for small cross sectional area and tight pack of Kevlar yarn, the achievable modulus of elasticity of a Kevlar rope could be taken as 62.5 % of the modulus of elasticity of the yarn which is known to be 124Mpa and in line with the % efficiency we consider in section 3.3.3

$$\Rightarrow \quad E_{kevlar} \approx 0.625 \text{ x } 124\text{GPa} = 77.5 \text{ GPa}$$

Based on the above information, the modulus of elasticity and the stretch coefficient of the two concept cables could be calculated according to the standard rating, elongation of a 1000m cable for a 5KN load applied and both ends fixed.

Case 1- Design Concept II

$$E_{Cable} = E_{armor}.\ \omega + E_{Kevlar}.\ (1-\omega)$$

$$\Rightarrow \quad = 82.8x\ 0.68 + 77.5\ x\ (1-0.68)$$

$$\Rightarrow \quad = 81.104\ \text{Gpa or } 77.30\ \text{Gpa (for stainless steel armor)}$$

But $\varepsilon = \Delta l/l = \sigma / E = \Delta l/l$

$$\Rightarrow \Delta l = l\ .\ \sigma/E$$

$$= l.\ (F / A_{Cable}\ )\ .\ 1/ E_{Cable}$$

$$= 1000\ x\ (5000\ N/ 31.08\ x\ 10^{-6)}\ x\ (1/ 81.104\ x\ 10^{9)}$$

$$= 1.98\ m / km\ \text{(or 2.08m/km for stainless steel armor)}$$

Case 2 – Design Concept III

$$E_{Cable} = E_{armor}.\ \omega + E_{kevlar}.\ (1-\omega)$$

$$\Rightarrow \quad = 82.8x\ 0.41 + 77.5\ x\ (1-0.41)$$

$$\Rightarrow \quad = 79.67\ \text{Gpa (or 77.38 Gpa for stainless steel armor)}$$

Using the same approach, the stretch coefficient will be:

$$= l.\ (F / A_{Cable}\ )\ .\ 1/ E_{Cable}$$

$$= 1000\ x\ (5000\ N/ 32.29\ x\ 10^{-6)}\ x\ (1/ 79.67\ x\ 10^{9)}$$

$$= 1.94\ m / km\ \text{(or 2.0 m/km for stainless steel armor)}$$

In reality, the Kevlar fiber griped with the armor wires, twisted over the copper core at relatively large lay length, and small pitch radius is not expected to have a noticeable amount of construction stretch. As it is known, a parallel laid Kevlar fiber will have theoretically a 0 % constructional stretch capacity as the ropes length is the same as the length of the individual fibers length, and this implies the stretch coefficient of such arrangement will come entirely from the elastic strain.

For our case, the individual Kevlar strands with a lay length of 81.46 mm and pitch diameter of 3.184 mm (design concept III) has only extra 0.24 % length than the cable itself and considered as too small to generate considerable constructional stretch. However, the steel wires with a lay length of 59mm and pitch diameter of 7.393mm will have an extra 7.447% wire length and upon a very small squeeze of the core, the extra length of the wire in the cable will start to slide and generate considerable amount of constructional stretch. In general, this large difference in constructional stretch capability between the steel armor and the Kevlar fibers could be modeled as shown in figure 3.11.

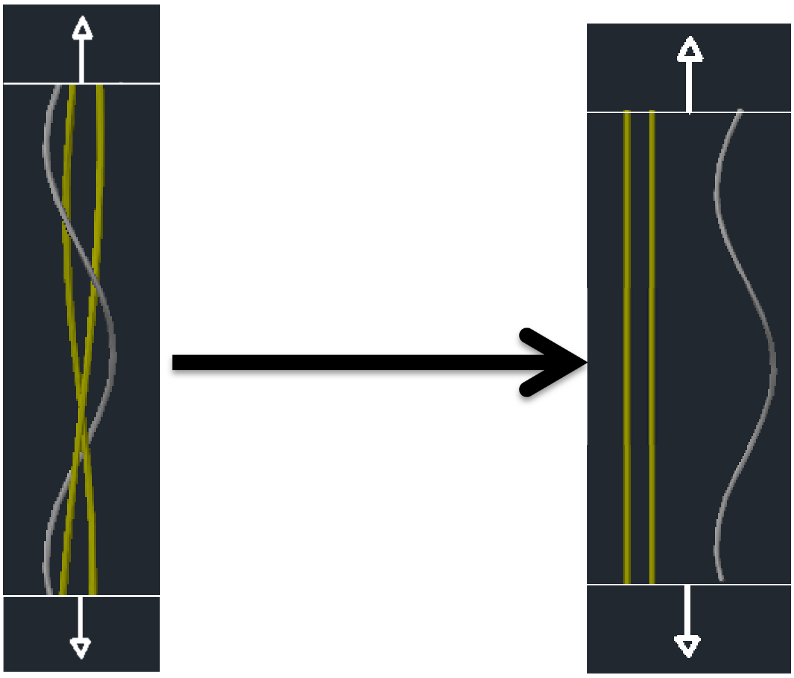


Figure 3.11: *Simplified model - constructional stretch difference between Kevlar and steel*

From this simplified model, we could understand that, for every unit force we apply, the Kevlar®49 fibers will start to elongate from the elastic stretch while the steel armors undergo constructional stretch until it consumes all the residual construction stretch capability. *The main idea is that, by controlling the constructional stretch coefficient of the steel armors (by adjusting the lay length of the steel armor),* the necessary delay could be achieved so as the steel armor could carry the desired load only at the peak value, e.g. at 60% of the cable breaking strength.

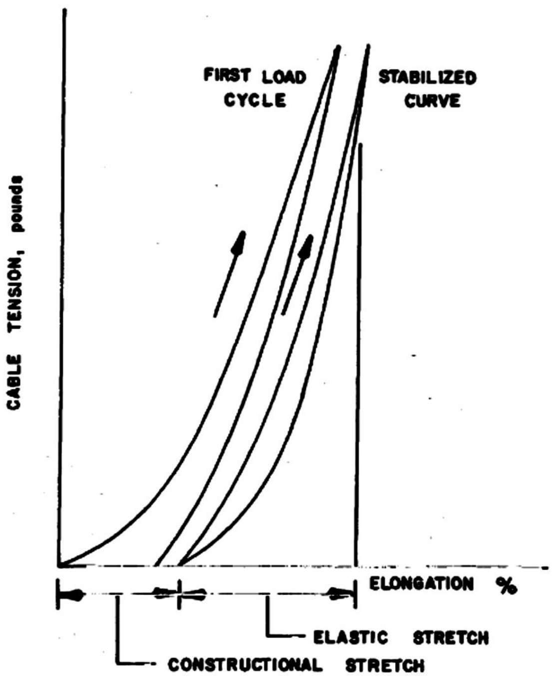


Figure 3.12: *Constructional and elastic stretch characteristics of a steel cable* (Gibson, 1999)

Now let us we calculate the pure elastic stress and the constructional stretch requirement of the two concept cables so as overstressing of the steel armor could be alleviated.

Case 1- Design Concept II

- **Regular steel Armor**

$\Delta l_{Cable} = (\Delta l_{Construction,\ armor} + \Delta_{elastic\ ,armor} \approx \Delta_{elastic\ ,Kevlar}$

$\Rightarrow \Delta l_{Cable} = \Delta l_{Construction\ ,\ armor} + l.\ (F_A/\ A_A.\ E_{Armor})$

$\Rightarrow$ 1.98m $= \Delta l_{Construction\ ,\ armor}$ + (1000 x (5KNx0.62/21.22x 207) Gpa

$\Rightarrow \Delta l_{Construction\ ,armor} = 1.98 - 0.71$ m

$= 1.27$m

- **Stainless Steel Armor**

$\Rightarrow$ 2.08m $= \Delta l_{Construction\ ,\ armor}$ + (1000 x (5KNx0.59/21.22x 193) Gpa

$\Rightarrow \Delta l_{Construction\ ,armor} = 2.08 - 0.76$ m

$= 1.32$m

Case II – Design Concept III

- **Regular steel Armor**

$\Rightarrow \Delta l_{Construction\ ,armor} = 1.94 - 0.645$ m

$= 1.3$m

- **Stainless Steel Armor**

$\Rightarrow \Delta l_{Construction\ ,armor} = 2.0 - 0.621$ m

$= 1.38$m

As we could see from figure 3.12, the constructional stretch consists of a large portion of the cable stretch in the beginning and this value could be controlled by painstakingly adjusting the lay length of the armor. For example, using a smaller lay length to pitch diameter ratio will give more constructional stretch though this in turn generates extra weight to the cable.

3.3.7. Rotational Stability of the Cable

Uncontrolled rotation of the cable during operation could result unintended events and also shorten the life time of the cable and have to be minimized as much as possible. The helix nature of the armor wires are main source of unbalanced torque. In general, the amount of torque generated on a cable is proportional to the load intensity, the pitch diameter of the cable, and the helix angle which the armor wires are laid over the core.

In order to balance the torque, cables and ropes are designed with two or more layers of armor wires which are oppositely laid so as the torque generated in one layer could balance the other. However, as the amount of torque induced in the inner and outer armors is quite different, it is will not be possible to entirely annul the net torque unless we have 3 or more layers. In our case, the presence of Kevlar fiber at the middle of the cable (small pitch radius) is found to be a challenge as the armor wires became dominant torque sources from their large helix angle and relatively large pitch diameter.

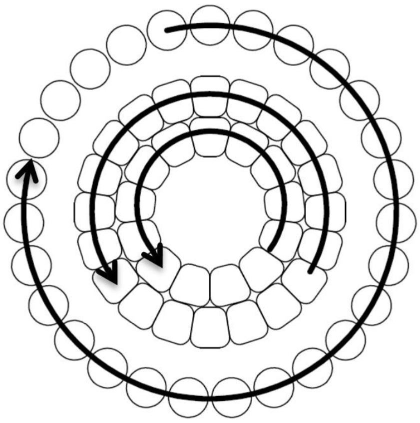


Figure 3.13: *Expected Torque distribution of the cable - Design Concept III*

In general, an applied vertical load (F_b) on a cable of pitch radius (R), and helix angle α will create a force component (Fc) tangent to the pitch diameter and shown in figure 3.14.

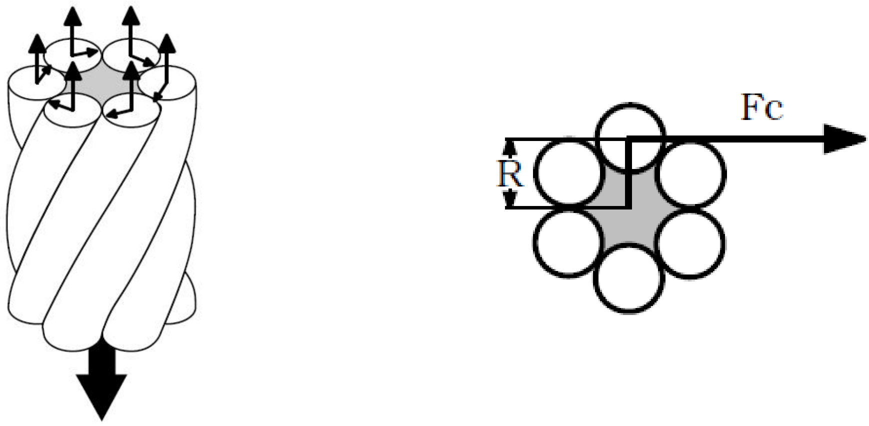


Figure 3.14: *The relation between an applied vertical load and its force components (Verreet, 1997)*

Taking a simple geometrical relationship, the different force component acting on the cable could be given as follows:

$$F_b/n_A = F_c/\tan\alpha$$

Moreover, torque(M) is a product of force and lever arm and as a result, the total force acting on a single layer of armor wires, or Kevlar strands at a pitch radius R could be expressed as follows:

$$M = n_A.\ F_c.\ R$$

If there are two or more layers of armor wires with opposite lay direction, the net torque will be sum of the individual layers taking one layer negative and the other positive. Based on the above argument, the expected torque on the cables discussed on the two design concepts will be as follows.

- ***Case I – Design Concept II***

Since the induced torque is a function of the applied load, we will try to calculate the value at the maximum practical load on the cable, e.g. 60% of the breaking strength of the cable so as we could understand its behaviour at the ultimate working condition. From our previous discussion, we have theoretically determined the breaking strength of the cable to be 59.75KN (regular steel armor) and also the load distribution between the armor wires and the Kevlar strands. The load distribution between the Kevlar fiber and the steel armor at 60 % of the breaking strength is found to be 37 % and 63 % respectively for this design concept.

⇒ Load on the steel armor = 0.6 x 59.75 KN x 0.63 = 22.59 KN

⇒ Load on the Kevlar fiber = 0.6 x 59.75 KN x 0.37 = 13.26 KN

However, we have two layers of armor wires, 27 x 0.787mm outer armor layer and 27x 0.617 mm inner armor layer. If a smooth load distribution is achieved, the percent load distribution on the two layers will be proportional to the cross sectional area of the wires since the number of wires is the same.

⇒ Load on the outer steel armor = 22.59 x (13.14mm2/21.22mm^2)
= 14 KN

⇒ Load on the inner steel armor = 22.59 - 14 KN
= 8.6 KN

From section 3.3.2, we have also determined the pitch radius and the helix angle of the outer armor and the inner armor wires and could be presented here as follows:

Description	60 % load , KN	Pitch radius , R	Helix angle , α
Outer armor	14	7.393/2	21.5
Inner armor	8.6	5.989/2	21.5
Kevlar fiber	13.26	3.188/2	7.0

Now we have all the necessary information to calculate the torque on the outer armor, inner armor, and the Kevlar fiber at 60% of the breaking strength of the cable.

- Torque on the Outer Armor:

$$M_{OA} = F_{\text{outer armor}} \text{ x } \tan \alpha \text{ x } R$$
$$= 14\text{x}10^{3}\text{x} \tan 21.5 \text{ x } 3.6965 \text{ x}10^{-3}$$
$$= 20.38\text{N.m}$$

- Torque on the Inner Armor:

$$M_{IA} = 10.14\text{N.m}$$

- Torque from the Kevlar fibers:

$$M_{KF} = 2.6 \text{ N.m}$$

Since the inner steel armor carries less torque, it has to be compensated by the Kevlar fiber and this is done by making the lay direction of the inner steel armor and the Kevlar fiber in the same direction. Based on this hypothesis, the net torque acting on the cable at 60% of the breaking strength will be as follows:

Net torque on the cable at 60 % load = $M_{OA} - (M_{IA} + M_{KF})$
= 20.38-(10.14+2.6)
= 7.64 N.m

This implies that, a net 7.64Nm torque is expected if the cable operates at 60% of its breaking strength and a swivel joint is recommended so as to absorb this rotation effect and without damaging the equipment's.

- ***Case II – Design Concept III***

Using the same approach as we did earlier, the three toque components acting on the cable at 60% of the breaking strength (regular steel armor) are found as follows:

- Torque on the Armor (only one layer):
  M_A = 27.18N.m
- Torque on Outer Kevlar Strands:
  M_{OK} = 4.43 N.m
- Torque on Inner Kevlar Strands:
  M_{IK} = 1.88 N.m

If the two layers of the Kevlar strands are laid in the same direction and opposite to the steel armor wires, the net torque acting on the cable at 60% of the breaking load will be as follows:

- Net torque on the cable at 60 % load = $M_{OA} - (M_{IK} + M_{OK})$
= 27.18 - (1.88+4.43)
= 20.86 N.m

This implies that, a net 20.86 N.m torque will exist towards the outer armor wires lay direction and has to be compensated at the winch by using swivels. However, in order to make some comparison, the unbalanced torque on the current Camesa 5/16″ cable at 60 % of the breaking strength was calculated as shown below.

The breaking strength of a regular steel armor cable under this category is rated as 53.3KN according to the manufacturer's catalogue.

- Load on the outer steel armor = 0.6 x 53.3 x (18/30)
  = 19.19 KN
- Load on the inner steel armor = 0.6x53.3 – 19.19 KN
  = 12.79 KN

From section 3.3.2, we have also determined the pitch radius and the helix angle of the outer armor and the inner armor wires and could be summarized as follows.

Description	60 % load , KN	Pitch radius , R	Helix angle , α
Outer armor	19.19	7.05/2	18.82*
Inner armor	12.79	4.79/2	18.82*

** Measured values from scrapped cable and true values could deviate slightly*

- Torque from the outer armor at 60% of the breaking load,

$$M_{OA} = 23.05 N.m$$

- Torque from the inner armor at 60% of the breaking load,

$$M_{IA} = 10.44$$

Since the two armor wires are laid in opposite direction, the net torque will be the sum of the two and taking one of them as negative.

- Net torque on the cable at 60 % load = $M_{OA} - M_{IA}$

$$= 23.05 - 10.44$$

$$= 12.61 N.m$$

From this we could understood that, the concept cable discussed under design concept III is expected to have a relatively higher unbalanced torque than the cable currently in operation. However, the consequence of this unbalanced torque in the newly designed cable (design concept III) could also be minimized using appropriate swivel joints.

3.3.8. Dimension & Material Content of the Insulation Jacket

- **Insulation Material**

In both concepts we discussed so far, we have one relatively thick insulation jacket and one thin insulation tape. The tape is primarily used to bind the copper conductors so as the Kevlar fiber could be laid in a smooth surface. The thickness of this insulation material is designed to be only 0.2mm and could be made of heavy duty and heat resistance polymide materials such as Nomex. As it is known, Nomex® is a brand name of DUPont and has a rated operational temperature range of -55 ^{o}C to +260 ^{o}C according to product specification listed in the company's web page.

However, the outer insulation jacket is supposed to have excellent wear and cut resistance property so as to resist the squeezing effect of the steel armor wires. If the expected working temperature is in the range of 149 ^{o}C, the plastic material Polyethylene could be used, else Tefzel® ETFE or Teflon® PFA based insulation jackets could be considered.

- **Constructional Dimension**

The armor wires compress the insulation jacket and create a peak and trough structure and as a result, the actual insulation thickness has to account the geometrical change so as the desired jacket thickness could be achieved. As we could see from figure 3.15, the final outer diameter DC will be different from the thickness of the jacket used for construction (DC′) and the recommended approach will be as follows (Wireline Works $_{INC}$, 2005):

$$DC = DC' + (2/3)\ d,$$

Where d is the armor wire diameter

However, for a cable with two layers of armor wires, the relation between the construction thickness of the jacket and the final thickness is given by the following mathematical relation (Wireline Works $_{INC}$, 2005):

$$DC = D - 2d_0 - 2d_i \quad \text{and} \quad DC' = [(DC + di)^2 - (N/2 \cos \alpha)\ di^{2}]^{1/2}$$

Where

N – Number of armor wires in the inner circle

α – the helix angle (lay angle)

d_i – wire diameter , inner armor

d_o – wire diameter , outer armor

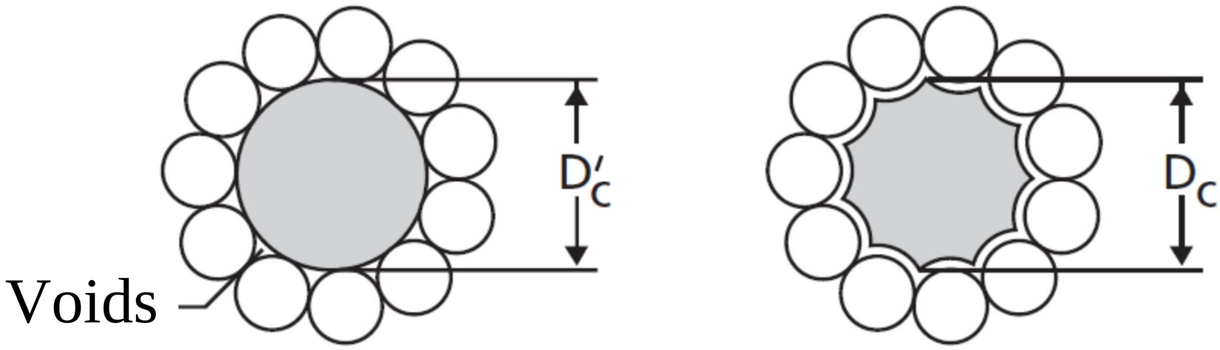


Figure 3.15: *Relation between constructional thickness and final thickness (*Wireline Works $_{INC}$, 2005)

Based on the above literature recommendation, the size of the insulation jacket during construction could be estimated as follows.

Case 1 – Design concept II

In this design concept we have two layers of steel armor wires with diameter of 0.787 and 0.617 mm. As a result, the outer diameter of the insulation layer could be estimated as follows:

$$\Rightarrow DC = D - 2d_0 - 2d_i$$
$$= 8.18 - 2 \times 0.787 - 2 \times 0.617$$
$$= 5.372$$
$$\Rightarrow DC' = [(Dc + di)^2 - (N/2 \cos \alpha)di^2]^{1/2}$$
$$= [(5.372 + 0.617)^2 - (27/2 \cos 21.5)0.617^2]^{1/2}$$
$$= 5.58mm$$

This implies, the insulation material should have an outer diameter of 5.58mm and inner diameter of 4.172mm or a thickness of 0.704mm.

Case 2 – Design Concept III

Since we have only a single layer of steel armor in this design concept, we use the first mathematical expression to relate DC and DC′:

$$
\begin{aligned}
& DC = DC' + (2/3)\,d \\
\Rightarrow \quad & = 6.606 + (2/3)0.787 \\
& = 7.13 \text{ mm}
\end{aligned}
$$

The outer insulation jacket is expected to be manufactured from an outer diameter of 7.13mm and inner diameter of 5.406mm or a constructional thickness of 0.86mm and higher than the net geometrical thickness, 0.6mm initially considered. If the cable is made of stainless steel armor, the thickness of the jacket has to be 100µm less than the respective high strength cables, so as to accommodate the conductive tape.

3.4. Recommended Drum Diameter

As it is known, a smaller sheave diameter will lead to more bending stress on the cable and could lead to premature failure of the cable. To avoid this, rope and cable handbooks have generated recommended sheave diameters for optimum fatigue life of cables and ropes running over drums.

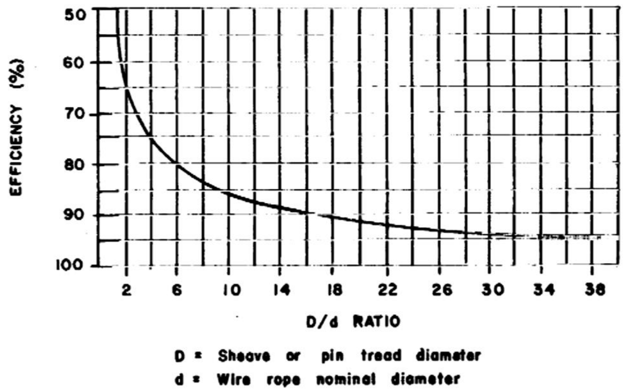


Figure 3.16: Approximate Strength Efficiency of Wire Rope when Bent Over Sheaves or Pins of Various Sizes (Gibson, 1999)

Moreover, the recommended sheave diameter for cables used in the wireline industry is expressed as follows (Moffatt et al., 2012):

- For steel based cables, the recommended groove diameter is from 1.0 to 1.04 times the wireline diameter.
- Grove shape is supposed to be: 135 to 150 ^{0}
- Recommended sheave diameter for depth less than 8000m, minimum sheave diameter is 400times the outer armor wire diameter (not the wireline)
- For depth greater than 8000m minimum sheave diameter of 600times the outer armor wire diameter.

The recommend sheave diameter for Kevlar based ropes is in the order of 40:1 to 25:1 ratio (diameter of the sheave (D) to the diameter of the Kevlar rope (d) (Simeon, 2001). In our case, we have two elements with different sheave diameter requirement, the Kevlar fiber and the steel armor. Consequently, the sheave diameter has to be the maximum of the two values and could be calculated as follows.

Case 1- Design Concept II

In this design concept, the outer steel armor is made of 0.787mm diameter wire and if assume the cable will not be more than 8000m, a minimum sheave diameter of 315 mm will be required. For the Kevlar fiber, taking the maximum recommended 40:1 ratio and a diameter of 4.172mm (outer surface of the fiber), the recommended sheave diameter will be 166.88mm. Comparing these two values, the sheave diameter is found to be governed by the steel armor wires and found consistent with the currently used drums of Altus Intervention.

Case 2 - Design Concept III

The only difference is that, in this case we will have Kevlar fibers with a relatively larger surface diameter than design concept II. As a result, the recommended sheave diameter for Kevlar fiber will be 216mm but still the drum diameter is governed by the steel armor, 315mm.

3.5. Termination Mechanism for the New Cable (Conceptual)

The termination mechanism for currently used monoconductor cables is performed as seen in figure 3.17. In this type of termination mechanism, the strength of the assembly depends on the number of wires terminated and this approach is used to ensure pullout of the cable at the tool head before the cable break elsewhere.

Figure 3.17: *Cable Termination in the currently used Monoconductor Cables* (Dunning, 2013)

Unlike of steel wires, Kevlar fibers and strands couldn't be terminated in reverse way as they most likely fail at the sharp bend. The best mechanism of terminating Kevlar based ropes is based on the spike - and-barrel arrangement as shown in figure 3.18. The main science behind this termination method is that, as the wage shaped spike squeezes the Kevlar fiber with the barrel, a frictional force proportional to the squeezing force will be generated. This type of termination technique is reported to give a cable head even stronger than the rope strength itself (Burgoyne, 1993)

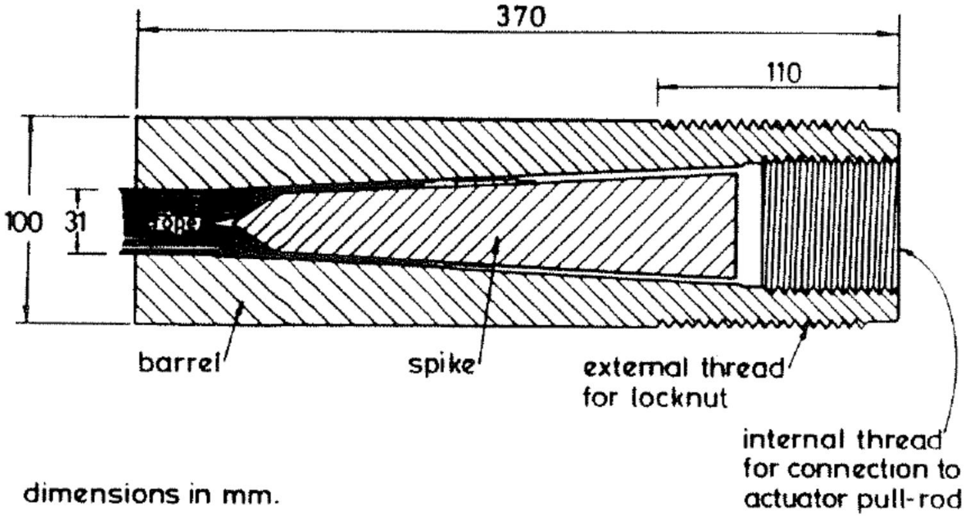


Figure 3.18: *Termination mechanism for a 60tonne break load rope* (Burgoyne, 1993)

This implies, we need a termination mechanism which suits for both the steel armor and the Kevlar. This could be done by extending the length of the currently used cone housing (with fishing neck) so as to accommodate the additional termination mechanism for the fiber and as shown figure 3.19. The length of the barrel is determined from the relation between the frictional force required and the breaking strength of the cable. As it is known, the frictional force generated is a function of the normal force and the coefficient of friction between the individual Kevlar fibers and also between the fiber and the wall of the barrel or the spike.

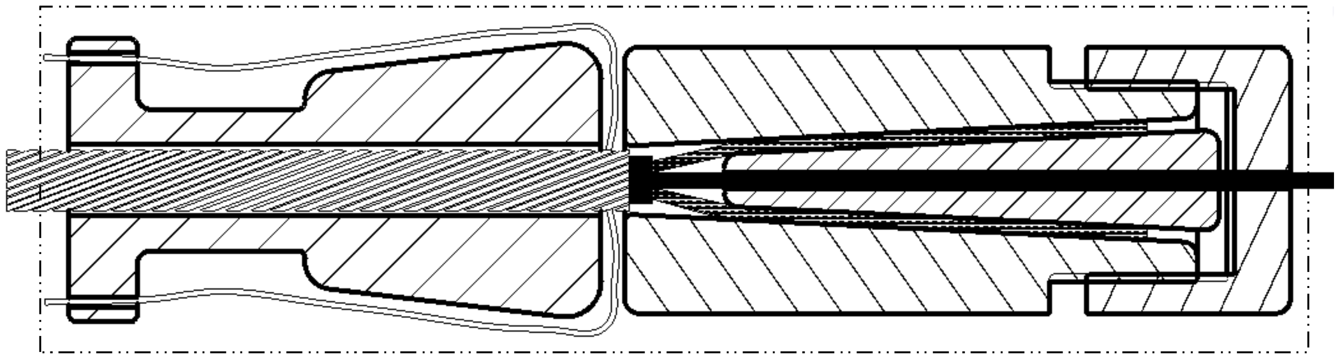


Figure 3.19: *Termination Mechanism of the New Cable © Yohannes/ AI/UIS)*

The dimension of the spike and the barrel could be estimated taking the maximum load on the Kevlar fiber and other recommended parameters from Kevlar rope termination hands books and research papers.

Case 1- Design Concept II

Taking the cross sectional area of the cable and the respective outer diameter of the steel armor wires and the Kevlar fiber, the respective dimension of the spike and the barrel will be as follows:

- Dimension of the Barrel

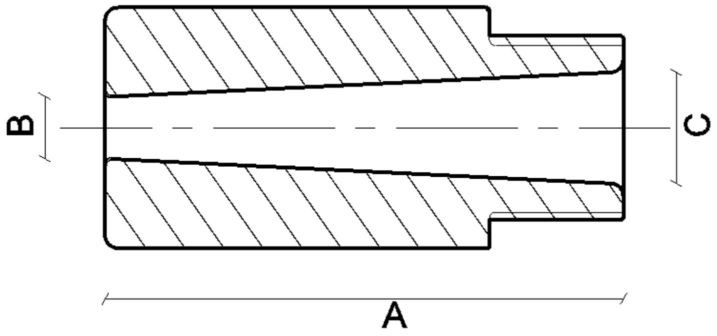


Figure 3.20: *Barrel for Kevlar Termination*

Table 3.11: *Summary of the barrel dimension*

No.	Dimension	Value (mm)	Remark
1	A	70.00	Assigned value, for iteration
2	B	4.50	Cable geometry + 0.3mm allowance
3	C	12.5	Calculated from geometry
4	Angle	3.8^0	Recommended value (Brown et al., 1999)

- Dimension of the Spike

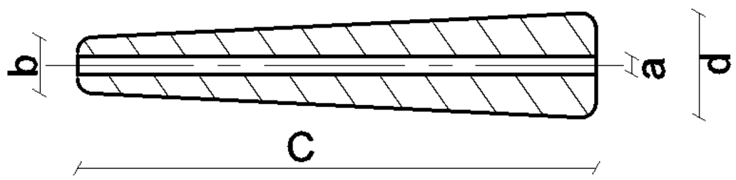


Figure 3.21: *Spike for Kevlar Termination*

Table 3.12: *Summary of Spike dimension*

No.	Dimension	Value (mm)	Remark
1	a	2.4	Cable geometry + 0.2 allowance
2	b	5.0	@20mm, offset
3	c	50.0	From geometry
4	d	11.6	Calculated from geometry
5	Angle	3.8^0	Recommended value (Brown et al., 1999)

Based on dimension set on table 3.11 and 3.12, the expected frictional force on the Kevlar termination mechanism under discussion could be calculated as follows:

- Maximum Contact area achievable from the spike:

$$A_{spike} = ((b + d)/2)*\pi \times c$$
$$= 1304mm^2$$

- Minimum grip force required (the same as the breaking strength of the Kevlar fiber):

$$F_{Kevlar} = F_{Frictional} \quad \cos 3.8^0$$
$$\Rightarrow \quad F_{Friction} = F_{bk}/\cos 3.8 \quad , F_{Kevlar} = 22.18KN, \text{ from section 3.3.3}$$
$$= 22.18/\cos 3.8$$
$$= 22.23KN$$

In this type of arrangement, we have two friction components, the friction between the individual Kevlar fibers and the friction between the fiber – metal contact which is either with the spike or with the barrel. However, as the surface area of contact between the barrel and the fiber is larger than the surface area of contact between the fiber and the spike, slip is only expected at the spike fiber interface. Moreover, research results conducted on the coefficient of friction between metal - Kevlar and Kevlar - Kevlar show that, the friction coefficient is minimal on the Kevlar - metal surface and slip occurs at the metal - Kevlar interface before the slip occurs between the fibers as stated by Brown et al. (1999).

$\Rightarrow$ Frictional force achievable at the spike - fiber interface will be as follows:

$$F_{Friction} = F_N \times \mu,$$
$$F_{Friction} = \sigma_N \times A_{spike} \times \mu$$

Where

μ - Coefficient of friction (between the fiber and the spike)

F_N - Normal force from the squeezing effect of the spike

σ_N - Normal pressure at the interface

$$\Rightarrow \sigma_N = 22.23 \text{ KN}/(1304 \times 0.22) \quad , \mu = 0.22 \text{ (Brown et al., 1999)}$$
$$= 77.5\text{Mpa, Normal Pressure}$$

This value is well below the capacity of Kevlar fibers which is in the order of 325Mpa (compressive strength) as seen on figure 2.4 of section 2.3.1. However, the location of the spike to get a pressure of 77.5Mpa could only be best determined on laboratory tests. However, as the thickness of the Kevlar fiber is too small, a slight forward movement of the spike is expected to generate a considerable compression effect. For example, if we move the spike 1mm forward, the Kevlar fiber will be compressed by 0.13mm which is quite significant knowing the total Kevlar thickness in this specific design concept is only 0.984mm.

Case 2- Design Concept III

Using the dimension of the cable under this category and all the steps we followed earlier, the dimensions of the spike and the barrel will be as shown in table 3.13.

Table 3.13: *Summary of the barrel dimension, design concept III*

No.	Dimension	Value (mm)	Remark
1	A	90.0	Assigned value, for iteration
2	B	5.7	Cable geometry + 0.3mm allowance
3	C	17.7	Calculated from geometry
4	Angle	3.80	Recommended value (Brown et al., 1999)

Table 3.14: *Summary of Spike dimension, design concept III*

No.	Dimension	Value (mm)	Remark
1	a	2.4	Cable geometry + 0.2 allowance
2	b	5.0	@20mm, offset
3	c	70.0	From geometry
4	d	14.3	Calculated from geometry
5	Angle	3.8	Recommended value (Brown et al., 1999)

3.6. Potential Service Inspection Technique

As it is known, both mechanical and electromechanical cables are prone to several forms of damage while at operation and a reliable inspection mechanism is highly needed if all the unintended consequences have to be avoided. Typical failure modes of electromechanical cables could have any of the following forms:

- Breakage of copper conductor or short-circuiting related problem
- Failure of armor wire or the yarn from excessive loading
- Abrasion and frictional wear of armor units
- Fatigue failure of armor wires
- Sulfide Stress Cracking (SSC) of the armor wires from H_2S attack
- Operational damage such as bird nesting, kinking, etc.

At the moment, a number of potential nondestructive testing (NDT) techniques are already reported by different scholars though it is only few of them which are believed to be under practical application according to the investigation of Rebel et al.(2005). Because of the hidden location of the Kevlar fiber in the design concept we are dealing with, visual inspection is not an option and the NDT inspection techniques listed below were assessed based on their relevance and maturity of the concept.

- Vibrational techniques
- Magentic resonance technique
- Conductive internal elements , and
- Fiber optics based techniques

Among these different options, the use of fiber optics seems the most likely solutions and also concluded by Rebel et al. (2005). Optical fibers will be included during the construction of the cable and presence of any elongation of the Kevlar fiber will have a finger print on strain sensors which in turn will be interpreted using relevant digital equipment's. However, it is my recommendation to further investigate the feasibility and the associated cost of this technique as a separate project work.

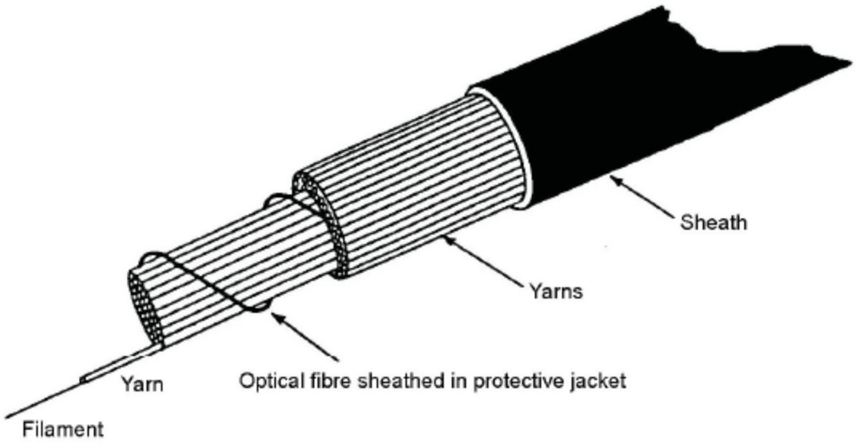


Figure 3.22: *Typical arrangement of inspection optical fiber sheathed in protective* (Rebel et al., 2005)

3.7. Well Intervention Simulation Software (Cerberus)

This software is currently used by Altus Intervention to assess the expected performance of both mechanical and electro-mechanical cables prior to actual operation. The software incorporates cable parameters such as strength, weight, stretch coefficient, etc. with the profile of the well to be intervened. In order to conduct the simulation and assess the performance of the two cables under discussion, the cable parameters are summarized and organized as seen in table 3.15.

Table 3.15: *Cable Parameter - 5/16" (Design Concept III)*

Regular Steel Armor		
Cable Type		
Nominal Diameter	8.18 mm	0.322 in
Weight in Air	219.31 kg/km	0.147 lb/ft
Weight in Water	168.31 kg/km	0.113 lb/ft
Stretch Coefficient	1.94m/Km/5KN	1.72 ft/Kft/Klbs
Breaking Strength	66.35 KN	14,938 lbf
Max. Temperature Rating	160 ^{o}C	320 ^{o}F
Drum Crush Caution		
Drum Crush Warning		

Moreover, the well parameter of the Åsgard Q-02 field with a reach length of 6115.0 m and well profile shown in figure 3.23 is used so as to evaluate the performance of the cables under discussion. The parameters of the other cables, design concept III (stainless steel armor), could be found in appendix A3.

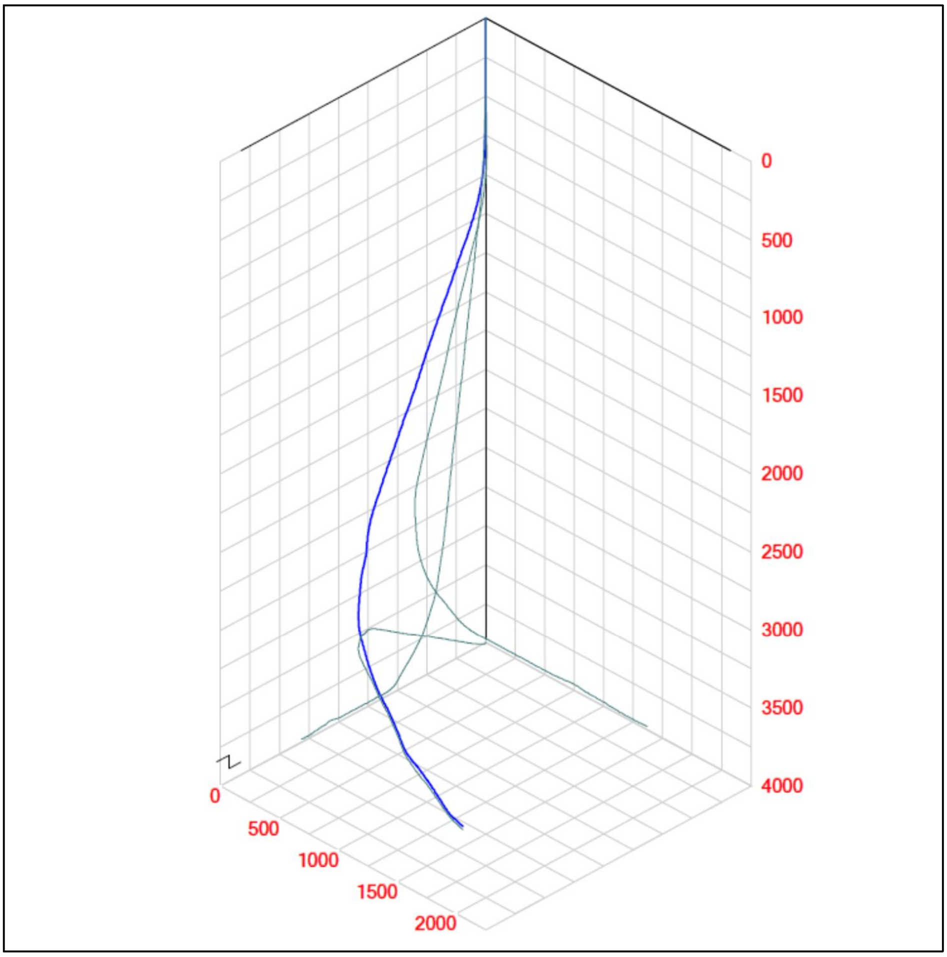


Figure 3.23: *Well Survey profile of Åsgard Q-02 field at 6115.0 m*

The simulation process is conducted for each category of cable and armor material and the report generated from the software is analyzed based on key performance indicators. The maximum pulling force required during *pulling out of hole* (POOH), and the safety margin of the POOH from the maximum safe work load (60%) currently practiced are used so as to compare the concept cables with the existing camesa cables of similar grades. Moreover, the pulling force required from the tractors to run into hole (RIH) is also extracted from the Cerbrus simulation report and discussed in detail (section 4.2).

3.8. Cost Estimation

As it is known, the concept cables discussed so far will only make sense if and only if there is an overall cost advantage either as a direct cost or indirect cost. The preliminary cost estimation is conducted based on the cost of the currently used cables as a bench mark and estimating the expected cost difference based on the features of the concept cables. As the estimation process is done without any consultation with potential manufacturers (as the design is currently under patent application), the values presented here after could probably have a significant deviation and the figures have to be considered only as indicative.

The main new cost component expected is to come from the cost of the Kevlar® 49 fiber which is largely associated with the initial fiber spinning cost rather than the final cable assembly process. As it is known, the cost of most fiber based products including carbon fiber is associated with the cost of the initial fiber production cost, whereas the cost of changing a once spun fiber to finished product is as easy as working with textile threads.

- **Cost of the Armor Material**

The current CAMESA cables of equivalent sizes (5/16 ″ - Monoconductor) cost USD 12.99/ft for Special Alloy Mono-Conductor Cable (1N32WTZ-S77) and USD 1.53/ft for Regular steel armor (1N32PTZ 5/16 Mono Carbon Steel Galvanized) cable [**Source:** information from the procurement department, Altus Intervention]. As we could clearly see, the main cost differences between the two cables exist on the type of armor material incorporated stainless steel vs. high strength regular steel, since the two cables are exactly the same size except the material constituent of the armor wires. This substantial cost difference between the two cables is used as a reference value to estimate the expected cost of the cables discussed under design concept II and design concept III.

Furthermore, the cost difference between the two cables could also be decomposed in to two, the extra cost of the material and the special manufacturing treatment requirement of stainless steel armor wires. As the cost of regular steel wire is in the order of 2USD/kg (http://www.alibaba.com/product-detail/galvanized-steel-wire-rope_1441993240.html), the current cost of regular steel based cables could be used as invariable cost components (cost of the copper conductor, the insulation material, transportation, ordering cost, cost of manufacturing, etc.) on assumption that all this costs are not dependent on the unit cost of the cable, rather on the size of the cable.

⇒ Cost difference between the two cables = 12.99 - 1.53 USD/ft
= 11.46 USD/ft or
= 37,600 USD/km

In addition to this, senior technical personnel at Altus Intervention (Fitje Bård) give his estimation of the cost breakdown of the extra cost associated to stainless steel cables as follows.

- 70 % of the extra cost is associated with the direct cost of the material (special alloy)
- 30% comes from the extra manufacturing process requirement

Now let us we calculate the expected cost of the armor wires in the two cables by taking the weight of the armor material we found in section 3.3.4. As we reduce the weight of the armor wires in both concepts, the reduction in cost from the armor wires and the extra cost from the Kevlar fiber has to be included. Now, taking the weight of the two layers of armor wires in the currently used 5/16″ Camesa cables (251.77 Kg/km), the reduction in the armor weight could be calculated as follows taking design concept II as a reference.

Armor weight reduction (kg/km) = 251.77 - 179.26 = 72.51 Kg/km

Now, taking the cost of a regular steel to be USD 2/kg, the cost reduction from a regular steel armor and also from a stainless steel could be calculated as follows:

- Cost of Stainless steel per Km ≈ 2x251.77 + 0.7x37, 600 ≈ 26,823.54 or
- Cost of Stainless steel per Kg ≈ 26,823.54/251.77 ≈ 106.54 USD/Kg

Table 3.16: *Summary of cost reduction from Armor weight reduction*

Design Concept	Armor weight Reduction/km	Cost reduction/ Regular Steel/km	Cost reduction/ Stainless Steel/km
Design Concept II	72.51 Kg	145.02 USD	7,725.22
Design Concept III	134.99 kg	269.98 USD	14,381.83

- **Cost of Kevlar® 49 Fiber**

As stated earlier, once Kevlar fibers are spanned as a yarn, the process of combining the yarn strands with the steel armor wires is not expected to be a complicated and costly process. Knowing the total weight of the Kevlar® 49 yarn required per km of the cable from our earlier discussion, the material cost of the Kevlar fiber could easily be estimated taking the current market price of a premium quality Kevlar® 49 fiber.

The currently referred market value of high quality Kevlar® 49 fibers is rated between 20-30 USD/Kg [reference] and taking the average of these value, 25USD/Kg for a longer and high quality fiber, the direct cost of the Kevlar® 49 will be as follows:

Table 3.17: *Summary of cost incurred from the Kevalr®49 fiber*

Design Concept	Weight of the yarn , kg/km	Material Cost , USD/Km
Design Concept II	15.26	381.50
Design Concept III	31.17	779.25

- **Cost of Conducting Tapes**

As discussed on section 3.3.5, the electrical resistance of the cable is relatively high if the armor material is made of stainless and as a result conductive tapes made of Ni-Cu was considered. The estimated weight of this conductive material per km of the cable is calculated and found to be 14.77kg/km for design concept II and 19.18kg/km for design concept III. Typical cost of such conductive tape (CHO-FOIL CCK-18-101-0100) is listed as £32.00 per roll (16.5m x 0.0787mm x 25.4mm). The total surface area of the cable per km is found to be 20.75m^2 for design concept III and 16.876m^2 for design concept II. Based on this simple approach, the cost of the conductive tapes is estimated to be in the order of £ 1312 for design concept II and £1600 /km for design concept III which is equivalent to 2210.59 USD/km and 2695.84 USD respectively according to the current exchange rate (http://www.electronicsarena.co.uk/companies/hitek-electronics-materials-ltd/products/tin-plated-copper-foil-tape).

- **Cost of Insulation Material**

The total amount of insulation material in the current cables is found to be nearly the same as the existing cables. In the currently used cables, we have a thick layer and often lay in two layers and over the copper conductors. Whereas in the design concepts we are discussing, we have a slightly thinner insulation layer but a larger outer diameter which makes the overall material cost nearly the same, please refer section 3.3.4 for the weight of the insulation materials.

- **Cost of Manufacturing**

As stated earlier, the flexibility and the fiber nature of Kevlar filaments is not expected to be both technologically intensive and time taking process. As a result, the cost of laying the Kevlar fibers over the core is expected to be simpler and cheaper than that of laying the armor wires. Based on this argument, the cost of manufacturing the current cables could be considered the same as the new cables with some marginal of error. Theoretically, this is about comparing steel cables and synthetic ropes at a larger scale though we fairly ignore this cost difference at this stage of the calculation.

- **Estimated cost of the Cable (Rough)**

Based all the above arguments, the cost of cable per 25,000 ft or 8.202 km length could be calculated as follows:

Case 1 - Cost of the cable under design concept II

- Regular steel armor

⇒ Cost of the new cable ≈ Base cost - cost reduction (armor) + additional cost (Kevlar)
≈ $ 38,250.00 - 145.02 x 8.202 + 381.5 x 8.202
≈ $40,189.61 /25,000 ft

- Stainless steel armor

⇒ Cost of the new cable ≈ $324,750.00 - cost reduction (only direct material)
+ Cost of Kevlar + Cost of conductive tape
≈ $324,750.00 - (7,725.22x 8.202km) (1/0.7)
+ 381.5 x 8.202 + $2210.59
≈ $239, 574.72 /25,000ft

Case 2- The cable under design concept III

- Regular steel armor:

⇒ Cost of the new cable ≈ $ 38,250.00 – cost reduction (armor) + cost of Kevlar
≈ $ 38,250.00 - 269.98 x 8.202 + 779.25x 8.202
≈ $42,435.07

- Stainless steel armor :

⇒ Cost of the new cable ≈ $324,750.00 - cost of armor reduction (material)
+ Cost of Kevlar + cost of conductive tape
≈ $324,750.00 - (14,381.83x 8.202km) (1/0.7)
+ 779.25x 8.202 + $2695.84
≈ $165,323.29 /25,000ft

In the above analysis, the potential decrement of the processing cost (30% of the cost difference) is not included in the calculation on assumption that, the processing cost might not be more or less the same as we still have 27armor wires and only 3 wires less and a smaller diameter. As a result, the processing cost of the stainless steel is not deducted with the decrement in the weight of the armor wires which is expected to have probably a positive effect in the overall cost of the cable.

Table 3.18: *Expected Cost of the Cable (rough estimation)*

Type	Regular Armor	Stainless Steel
1N32PTZ	$ 38,250.00	-
1N32WTZ-S77	-	$324,750.00
Concept II	$40,189.61 or ↑5.07 %	$239, 574.72 or ↓26.22 %
Concept III	$42,435.07 or ↑10.94%	$165,323.29 or ↓49.09 %

4. RESULTS AND DISCUSSION

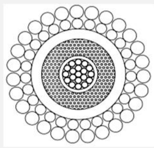
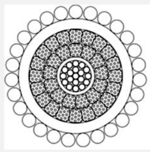
4.1. Improvement on Major Operational Parameters

In the introduction section, we have clearly stated the limitations of the currently used cables and also we have defined the objectives and goals of this project work. In order to assess the potential of the new design approach in addressing our initial target, a detailed performance evaluation of the concept cable is conducted and presented. The strength of the cable and its weight per unit length are two of the most important operational parameters and could be used as performance indicators. As clearly stated in section 1.3, it is our main interest either to reduce the cable weight or increase the strength of the cable or both. For this reason, the theoretical values we found in section 3.3.3 and 3.3.4 are compared with the catalogue values of the currently used equivalent grade cables and presented as follows.

4.1.1. Enhancement on the Cable Breaking Strength

As referred on Appendix A1 and A2 , the rated breaking strength of the two most commonly used 5/16" Monoconductor cables are 53.3KN for high strength cable (e.g.1N32) and 45.4KN for corrosion resistance cables (e.g. 1N32 S77). Comparing these values with the theoretical breaking strength of the two design concepts we calculated earlier, we will find the results shown in table 4.1.

Table 4.1: *Comparison of breaking strength© Yohannes/UiS/AI*

Armor Material	Design Concept II 		Design Concept III 	
	Breaking Strength	% Change	Breaking Strength	% Change
• High Strength	59.8 KN	↑12.2%	66.3 KN	↑24.4%
• Stainless Steel	54.2 KN	↑19.4%	62.9 KN	↑38.5%

From table 4.1, we could understand that, the theoretical improvement on the strength of the cable is quite significant mainly for design concept III which could reach up to 24.4% if the armor is made of high strength regular steel or up to 38.5% for corrosion resistance stainless steel armor.

In general, getting a high strength and corrosion resistance cable at the same time could be considered a breakthrough as the current cables are either relatively strong or corrosion resistant but compromised strength. In this sense, the use of Kevlar®49 fiber in the new design approach improves the strength of corrosion resistance cables significantly as Kevlar's strength is independent of the well medium. Overall, we could conclude that, design concept III or changing the cable from two layers of armor wires to a single armor wire to the best way of improving the breaking strength of currently used cables.

As seen in the same table, the corrosion resistance grade of the cable from design concept III to be about 16.05 % stronger than its counterpart (design concept II). However, the difference between the two concepts is limited to 10.87 % if the armor wires are made of high strength steel. In summary, evaluating additional parameters (e.g. weight, electrical resistance, stretch coefficient, cost, etc.) will be necessary before we conclude design concept III as the best possible design approach at this point of time.

4.1.2. Reduction in Cable Weight

The second most important goal we set at the beginning was to look for the means to reduce the cable weight without compromising the strength of the cable and its overall size. In making the evaluation, the rated weight of the currently used camesa cables (e.g. 1N32 S77) are compared with the theoretical weight of the two concept cables calculated in section 3.3.4 and summarized as follows.

Table 4.2: *Summary of the weight comparison*

Description	Concept Cable II		Concept Cable III	
	Regular Steel	Stainless Steel	Regular Steel	Stainless Steel
Weight in Air , kg/km	242.46	254.41	203.78	219.31
Weight in Water, kg/km	191.46	203.41	152.78	168.31
% weight change , Air(water)	↓ 17.53(21.2)	↓13.5(16.3)	↓30.7(37.1)	↓25.4(30.7)

Note: *the weight of the current cables is around 294kg/km in air and 243kg/km in water (*Camesa, 2013)

From table 4.2, we could learn that, a weight reduction up to 17.53 % in air could be achieved from design concept II and up to 30.7 % in air from design concept III. The main reason behind this significant weight reduction is associated with the light weight of Kevlar® 49 yarn and the associated armor reduction we made in the design approach we followed. In reality, this weight reduction is quite significant as it minimizes the amount of force required to pull the cable both at the winch during pullout and also by the tractor during descending in deviated wells.

In practical terms, this reduction in weight could be indirectly interpreted as improvement on the working strength of the cable since more proportion of the cable strength is now used for the actual work (e.g. pulling the tool string) instead of supporting the cable weight itself. For example, a 30.7 % reduction in cable weight is equivalent to a reduction of 90.26kg/km and if we consider a 5km cable, the reduction will be 451.29kg or 4.43KN. Converting this value to the 50% allowable working strength of the current 1N32 S77 cables (22.7KN), it will be equivalent to a net gain of 19.5 % working strength. Summing this value with the change in strength we found earlier, 38.5%, we will get a total of 58% improvement on the strength of the cable. However, the CERBRUS simulation software best combines the two parameters (weight &strength) and we will discuss this in section 4.2.

As a summary, moving from a two layer armor wire to a single armor wire will have a significant effect in reducing the weight of the cable and this in turn improve the actual (available) working strength of the cable. Furthermore, design concept III is expected to give us up to 15.94 % lighter cable than its counterpart, design concept II. This means, the cable discussed under design concept III excels both in strength and weight though still we need to further investigate it performance from the perspective of other parameters, namely electrical resistance of the armor and rotational stability.

4.1.3. Cable Stretch Coefficient

One of the shortcomings of the cables designed in both concepts is found to be their relatively large stretch coefficient compared to the currently available cables. The problem is associated with the incorporation of the Kevlar fiber, which is known to have a marginally larger stress - strain value within the elastic region of the steel wire. Knowing the stretch coefficient of the two categories of cables currently in use, 1.35m/km/5KN (high strength version) and 1.8/km/5KN (corrosion resistance version), a comparison table as shown below is established.

Table 4.3: *Stretch coefficient comparison*

Description	Type of Armor	Theoretical stretch Coefficient (m/km/5KN)	% Change
Concept II	Regular steel	1.98	↑46.67
	Stainless steel	2.08	↑15.56
Concept III	Regular steel	1.94	↑43.70
	Stainless steel	2.00	↑11.11

The two concepts cables are found to have a higher stretch coefficient than currently used camesa cables as seen in table 4.3. However, the adverse impact of this relatively large stretch coefficient is not shown up in the simulation software though still it needs to be further investigated once a prototype cable is developed. One of the consequences of large stretch coefficient is associated with short circuiting of the cable though this is not expected to be a problem in our case as the Kevlar fiber isolates the copper core from the steel armor in addition to the insulation materials. However, some have also forwarded their concern on the quality of logging data on assumption that the cable will result uneven speed of the tool string. Overall , its seem there is a need to wait the actual testing so as to fully understand the level of impact the extra stretch may give us.

4.2. Results from the Simulation Software and Anticipated Achievements

As stated in section 3.7, values such as RIH and POOH are potential indicators of the performance of a given cable under a known well configuration. As it is known, if the well has some deviation, the descending processes are likely handled by the pulling actions of tractors and lighter cable is always a preference if possible. Furthermore, the pulling force required at the winch is also largely dependent on the weight of the cable in addition to the tool string weight and the associated frictional resistance. As a result, the lighter the cable, the smaller the POOH value and the numerical figures found from the simulation software are summarized as follows.

4.2.1. Assessment Based on POOH Value

The POOH value found from the Cerberus simulation software for the concept cable (III) and also the currently used 5/16″ Monoconductor Camesa (both in regular steel armor) are depicted as follows.

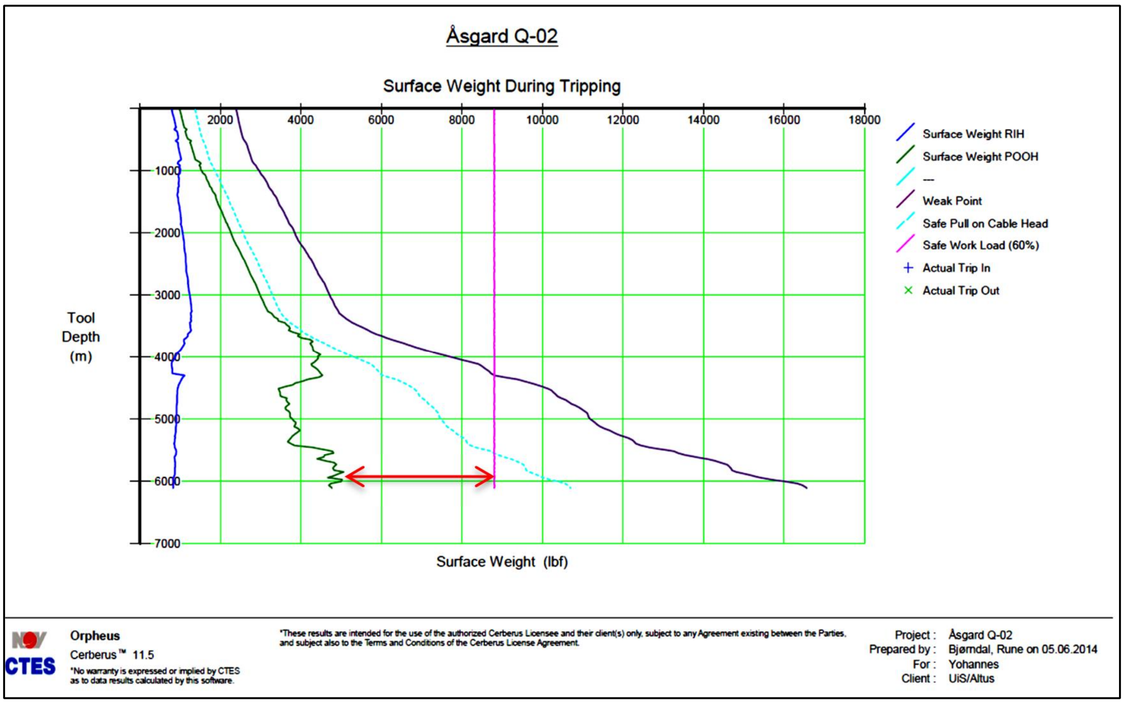


Figure 4.1: *Surface Weight during Tripping - Design concept III (regular steel armor)*

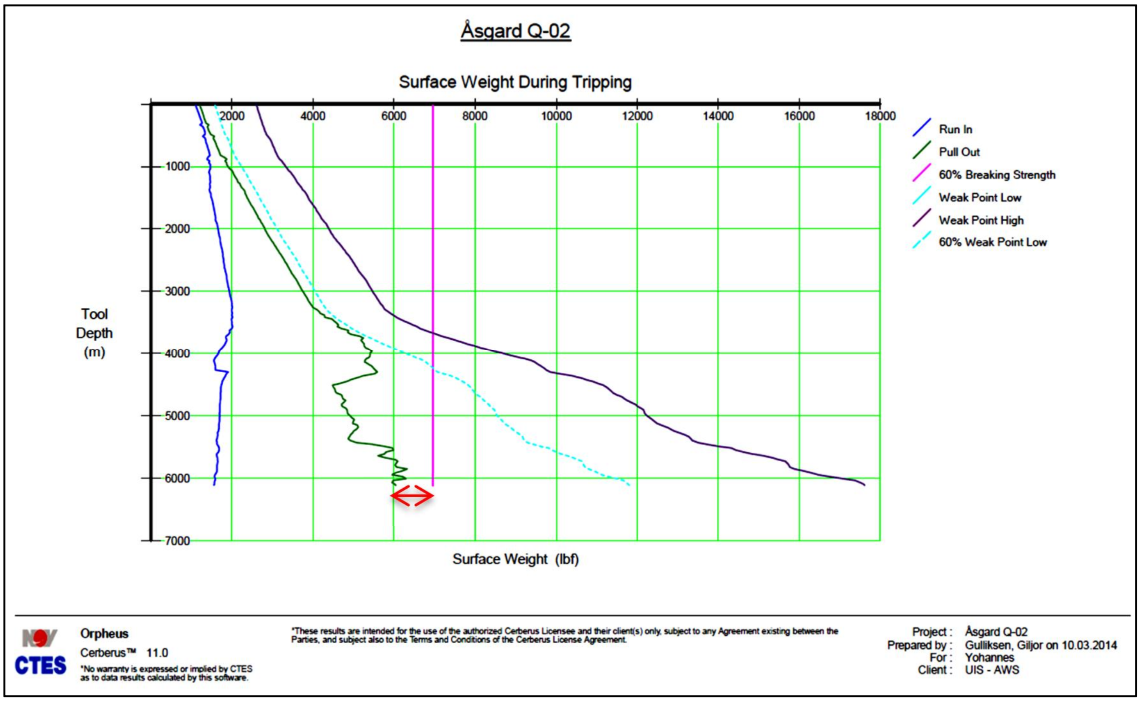


Figure 4.2: *Surface Weight during Tripping – Camesa 5/16" (regular steel armor)*

From figure 4.1 and 4.2, we could understand that, the maximum POOH value of the cable under design concept III is found to be around 5,000lbf or nearly 80% of the POOH value we will have for the camesa cable (6,300lbf). Moreover, the clearance of the maximum POOH value from the 60% safe work load could be clearly seen from the two figures(marked in red arrow) which is found to be 3,962.8 lbf for concept cable III and 700 lbf to the currently used camesa cable. This in turn could be interpreted as, either a higher degree of operational safety or extra capacity to attach more tool string or, capability to operate even more complicated wells than Åsgard Q2.

The most interesting performance difference is found when we consider the corrosion resistance version of the two cables under comparison. As it is known, the currently used cables have even lower breaking strength than the high strength version. As a result, the cable under this category is found unable to handle the job as the 60% strength is lower than the maximum POOH value. However, the newly designed cable (design concept III) with corrosion resistance stainless armor is found to handle the job as seen in figure 4.3 though the safety margin is slightly reduced compared to the high strength version we discussed in figure 4.1.

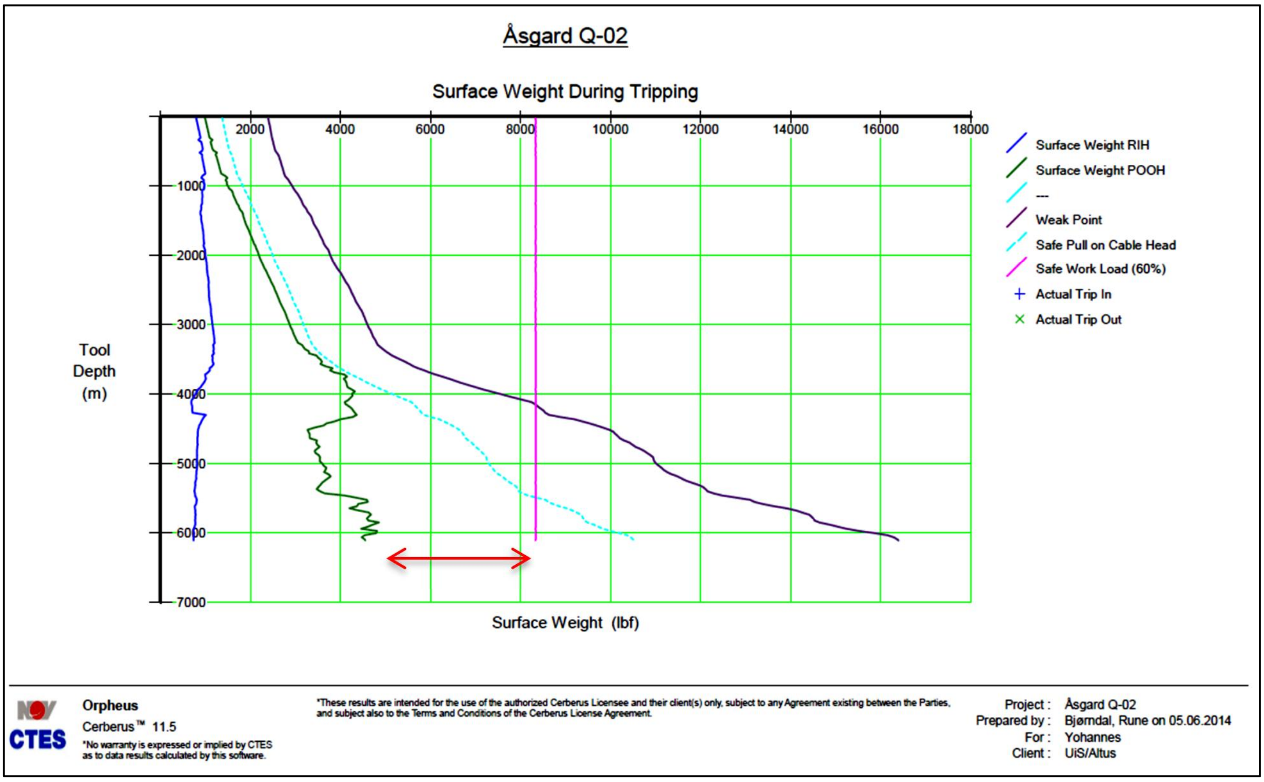


Figure 4.3: *Surface Weight during Tripping – Design Concept III (stainless steel armor)*

Overall, concept cable III seems capable of handling the job even with corrosion resistance steel armor, unlike of the currently used camesa cables of the same category and size.

4.2.2. Maximum RIH Value

The performance of the two concept cables could also be assessed from the perspective of the towing force required to descend in to the well, if the well has a deviated section as in the case of Åsgard Q2 field. Normally, the RIH value is associated with the cable weight taking all other parameters constant and the heavier the weight of the cable, the larger the frictional drag resistance will be. In general, the effect of the cable weight on the RIH value could be perceived from figure 4.4 and 4.5.

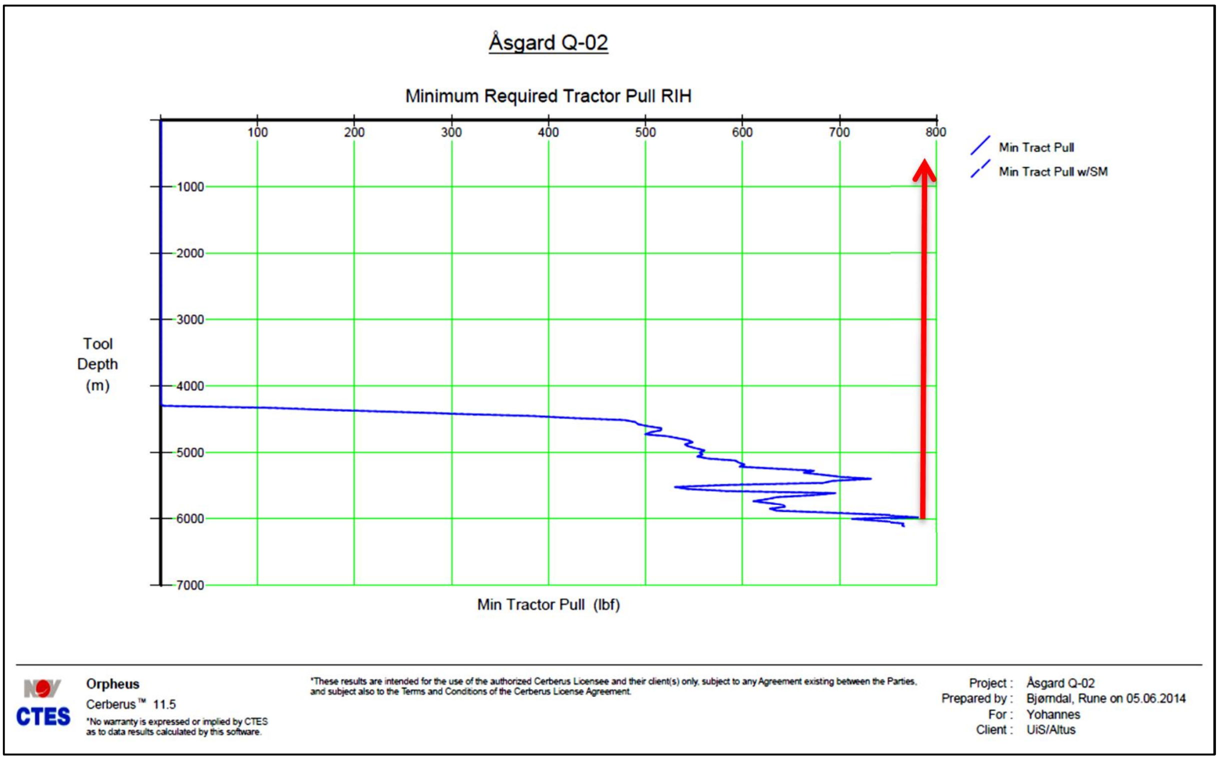


Figure 4.4: *Minimum required Tractor Pull (RIH) - Design Concept III-Regular steel armor*

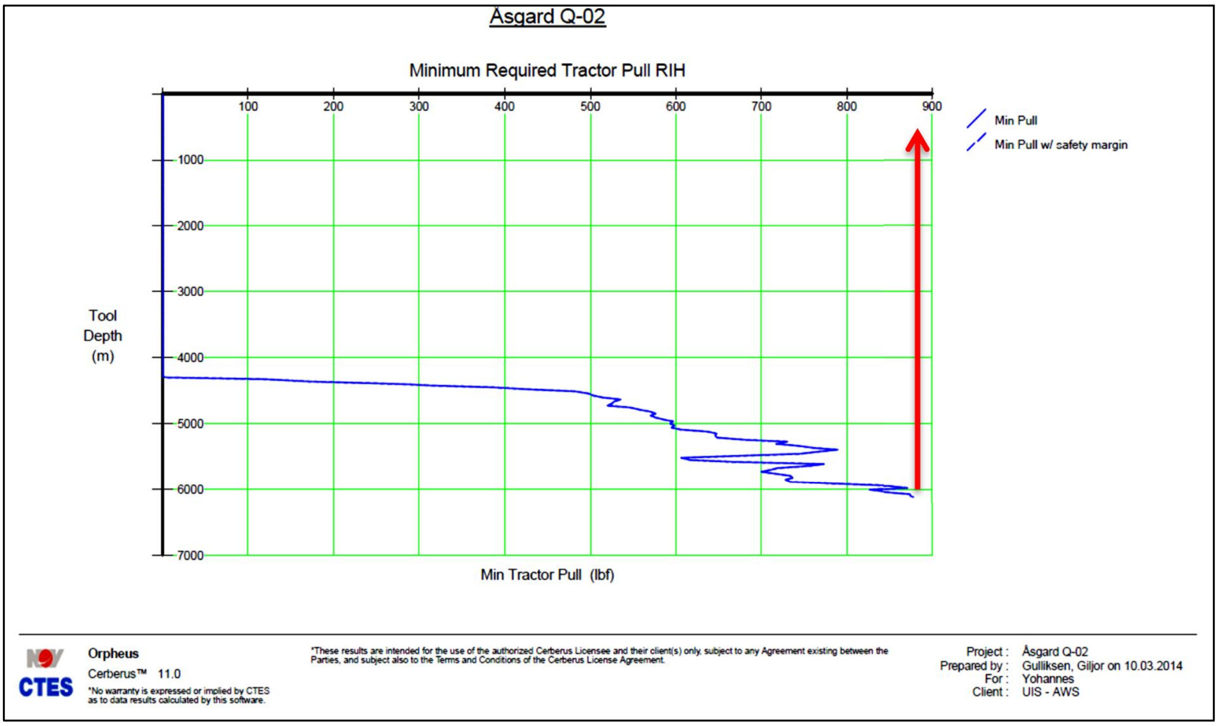


Figure 4.5: *Minimum required Tractor Pull (RIH) - Camesa 5/16" -Monoconductor*

To reach a total length of 6115m's with the current cables, a tractor RIH of 879 lbf will be required. Whereas, the value found from design concept III shows that, the tractor pull required to reach the same depth to be 781 lbf or 98 lbf less and could have a significant effect depending on the type of tractor we use. In summary, the cable designed under design concept III is found to outperform the existing cables from the two key operational evaluation aspects, POOH and RIH value.

4.3. Enhancement on the Corrosion Resistance of the Cable

In general, the concept cable we designed are expected to have superior performance over the currently used cables since the Kevlar®49 fiber we use is immune from potential corrosive gasses and fluids due to its inherent material property and also from the design approach we followed (shielded by a protective plastic jacket). However, the corrosion resistance property is better measured on the % improvement we achieved on the strength of stainless steel grade cables as the main issue is found to be getting a corrosion resistance cable without significant strength and also lower cost.

Table 4.4: *Improvement in corrosion resistance grades of the cable*

Armor Material	Design Concept II		Design Concept III	
	Breaking Strength	% Improvement	Breaking Strength	% Improvement
Stainless Steel	54.2 KN	↑19.4%	62.9 KN	↑38.5%

Overall, the H_2S related problem which is found to be a main problem of the currently sued cables is associated with lack of material which is both corrosion resistance and strong, and also affordable. As a result, the use of Kevlar® 49 fiber as load carrying member and corrosion resistance steel as armor will enable us to improve the performance of the currently used cables significantly and also a potential cost saving (section 4.8).

4.4. The Perspective of the New Cable in Alleviating Electrical Related Problems

Electrical related problems reported in the current cables are mainly associated with the corrosion resistance version the cable as it is known to have a higher armor resistance (36.9Ω/km) and also short circuiting related problem. As a result, the potential of the concept cables in alleviating electrical related problems could be assessed from two broad perspectives:

1. Alleviating short circuiting related problem and ,
2. Lowering the electrical resistance of the armor

In this regard, the steel armor and the copper conductors being separated by a two layers of insulation materials and a cut resistance Kevlar ® fiber, short circuiting related problem is not expected in the newly designed cables. As it is known, the excessive squeezing force of the armor on the plastic insulation material leads to tearing of the layer and hence short circuiting of the cable.

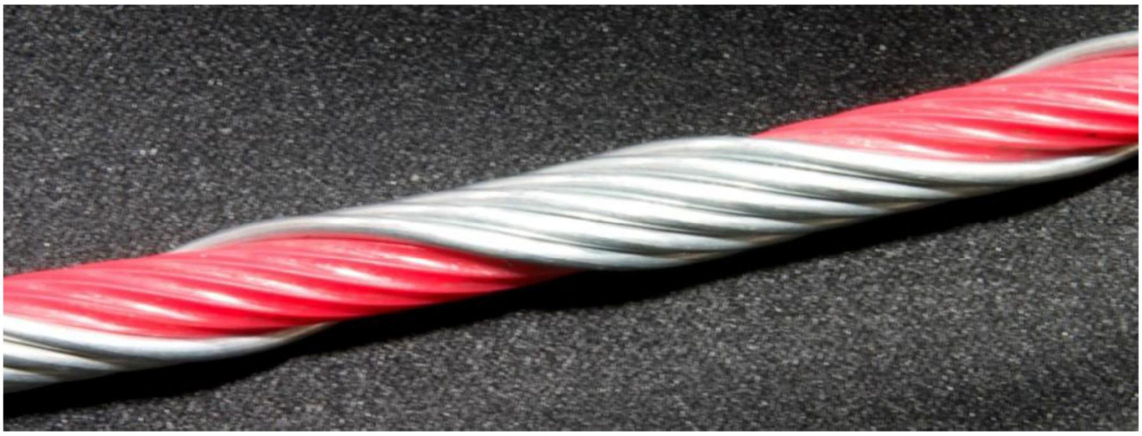


Figure 4.6: *High risk of electrical shorting of the cable from tear of insulation (*Moffatt et al., 2012)

Unfortunately, an overall increase in the electrical resistance is observed in the concept cables and could be considered as the main side effect of replacing the steel armor wires with kevlar®49 fiber. However, the electrical resistance of the concept cables could be maintained within an acceptable range by using conductive tapes which are ultra-thin, corrosion and high temperature resistance. Knowing the electrical resistance of the currently used camesa cables to be, 6.9 Ω / km for regular steel and 36.7 Ω /km for stainless steel armor, a comparison as shown in table 4.5 could be established.

Table 4.5: *Comparison of Electrical Resistance, armor*

Design Concept	Armor Resistance , Ω/km	
	Regular Steel	Stainless Steel & Conductive tape
Design Concept II	9.79 (↑ 42%)	18.92 (↓48)
Design Concept III	15.81 (↑ 129%)	18.75 (↓ 49)

From table 4.5, it is evident that, the electrical resistance of the armor is within the workable range even without using a conductive tape as long as the armor wire is made of regular steel though a significant increment is still registered. However, a dramatic and unacceptable increase in the electrical resistance is seen if the armor is made of stainless steel and the use of a conductive tape is found mandatory if the electrical resistance of the armor has to be kept within the acceptable range. Though currently available camesa cables such as 7J46 use conductive tape to improve electrical property, detail information from manufacturing companies seem necessary to fully characterize and understand the exact nature of these conductive tapes.

As a summary, the concept cables are found to have a higher prospect of alleviating short circuiting related problems though the dramatic increment in armor resistance brings additional design feature (conducting tapes).

4.5. Potential to Address Gas Break Through Related Problem

Since the diameter of the steel armor is limited to 0.787 mm, the cable surface is expected to be smoother and hence less grease pressure will be required to seal the annulus area between the cable and the stuffing box orifice. In reality, this could be calculated based on the void space between the currently used cables and the newly designed concept cables.

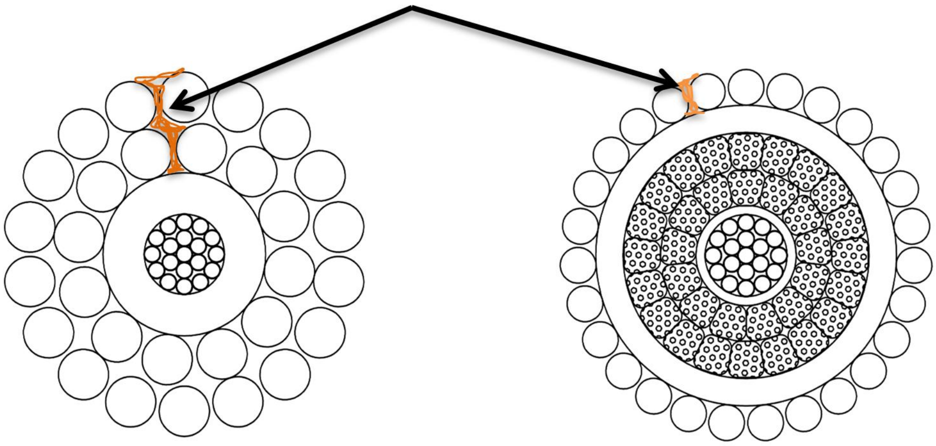


Figure 4.7: *The relation between armor wire diameter and gas breakthrough ©Yohannes/ UiS /AI*

Theoretically the void space we are supposed to seal with grease (only the void space between the adjacent armor wires, not the clearance between the cables outer diameter and the orifice) could be calculated as follows:

- Currently used cables

$$\text{Void Area} = \text{Area of the annulus} - \text{area of the 30 armor wires}$$
$$= \pi/4(D_0^2 - D_i^2) - \pi/4\,(n_A x\, d^2)$$
$$= \pi/4[(8.18^2 - 3.66^2) - 30x1.13^2]$$
$$= 11.95\text{mm}^2$$

- Cable under design concept II

$$\text{Void Area} = 8.68\text{mm}^2$$

- Cable under design concept III

$$\text{Void Area} = 5.14\text{mm}^2$$

From these three simple calculations, we could understand that, the cable under design concept III is expected to have a void space of only 5.14mm^2 or 43% of the currently used camesa cables. As a result, the problem of gas breakthrough (note that the pressure could be hundreds of bars) from loss of grease pressure at the stuffing box is expected to be minimal. Moreover, the consumption of grease will be reduced significantly as the grease is basically transported from the grease stuffing box to the well or to the platform surface through void space between the two adjacent armor wires. In Riserless wells, regulatory bodies force operators to use green grease (as it flows to the sea) and known to cost much more than the regularly used grease. As a result, the concept cables not only minimize gas breakthrough related problem but also will have an effect in reducing the cost of grease.

4.6. Improvement in the Expected Life Time of the Cable

- Fatigue Life Time of the Cable

The other positive result expected from the new cable design approach comes from the expected fatigue life of the concept cable, mainly concept cable III. As seen from figure 4.8, the fatigue life of Kevlar is much higher than the fatigue life of steel armor wire. The American Bureau of Shipping (2011) refer the fatigue life of Kevlar ® 49 around 10 million cycles (for a typical load range of 170 – 1700 N.mm$^{-2)}$ while steel only reach this life time for a load range of 100 -1000 Nmm^{-2}. This implies, fatigue failure will be unlikely for the Kevlar fibers as the 60% of the breaking strength is much lower than this value though well intervention cables are generally known to have very limited overall useful time.

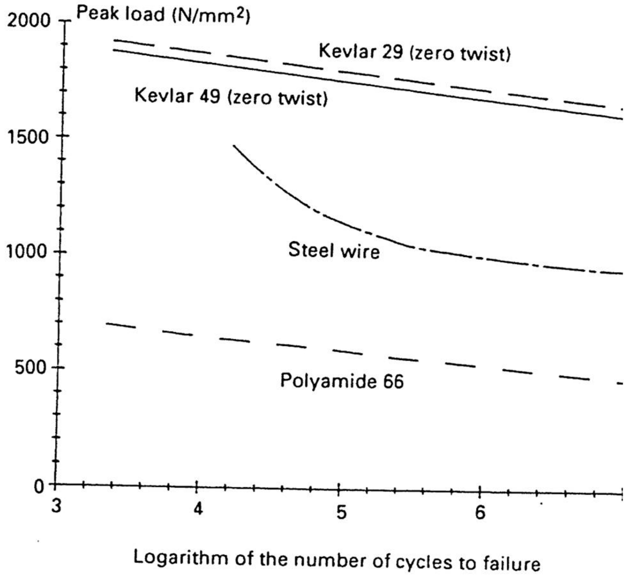


Figure 4.8: *S- N curves for tension – tension fracture of Kevlar yarn (Burgoyne, 1993)*

In addition to this, the fatigue life of steel armor wires is dependent on the size of the wire, the larger the diameter of the wire, the less fatigue resistance the wire will be as stated by the wire rope company , CCISCO(2014). As a result, reducing the armor wire size from 1.13mm to 0.787mm is expected to have a positive effect towards improving the fatigue life of the cable.

- Frictional Wear

As it is known, the rate of frictional wear is a function of material property, geometry of the meshing parts, coefficient of friction between the two rubbing surfaces, and also the normal force between the two bodies. In the currently used cables, damage of the armor wire from frictional wear is not reported as a problem though it could be a cause of concern in the new design concepts as the size of the armor wires is substantially reduced.

However, the undesirable effect of having smaller diameter wires is expected to be balanced from the reduction in cable weight and also the relatively large number of outer armor wires and found it unrealistic to make conclusion in either way. As a result, I refer this part to be investigated further either using relevant software models or experimental works so as to understand the point of balance between frictional wear rate and cable parameter (weight, armor size and number of wires).

4.7. Overall Operational Change Requirement

As it is known, adoptability of new products are highly dependent on their conformance to existing tools and equipments so as significant change will not be required at operational level. For this reason, attention has been given so as the overall change incorporated in the newly designed cables is kept minimal. However, two key operational changes are identified, cable head and service inspection technique.

- **Cable head**

As we discussed in section 3.5, a slight modification in the cable head is required so as to terminate not only the steel armor but also the Kevlar fiber. As the current cable heads are only designed to accommodate steel wires, extending the cone housing (with fishing neck) up to 10 cm will be required. However, this is not expected be to be a main problem as the associated cost is estimated only few hundred dollars and a onetime shopping.

- **Inspection mechanism**

Unlike of steel cables and ropes, the use of high strength synthetic ropes has a short history and thus the inspection methods are largely under development. However, different scholars have come up with different ideas though the use of hairy optical fibers in combination with the Kevlar strands seem the dominating inspection technique currently under implementation for applications such as mooring lines and bridge tendons. Optical fibers imbedded within the Kevlar strands are reported to be capable of generating recognizable signals for any abnormal extension of the Kevlar fiber lay length in the same manner strain gauge measurements function. However, the inspection method currently practiced for steel armor wires (torture test and visual inspection) could be practiced in collaboration with the fiber inspection mechanism.

4.8. Economical Feasibility of the Concept Cable

At last but not least, the expected cost of the two cables designed and compared with the market price of the currently available cables is presented as shown in table 4.10. Though a significant deviation is expected, the values could be used as preliminary indictors on the economic feasibility of the concept cables. In general, a major direct cost saving is expected on H_2S resistance cables as the reduction from the cost of the armor material out pass the cost we incurred from the Kevlar®49 fibers. For comparison purpose, the cost of the currently used cables, $ 38,250.00 and $324,750.00, for high strength (1N32PTZ) and corrosion resistance (1N32WTZ-S77) cables respectively is used as a bench mark.

Table 4.6: *Summary of the cost comparison*

Type	Regular Armor	Stainless Steel
Design Concept II	$40,189.61 or ↑5 %	$239, 574.72 or ↓26 %
Design Concept III	$42,435.07 or ↑10%	$165,323.29 or ↓49 %

As seen from the table, the concept cables designed are expected to have a cost increment in the order of 5% to 11% if the armor material is made of high strength regular steel. The main reason for this is associated with the relatively higher cost of Kevlar®49 compared to the cost saving we achieved from removing a substantial amount of steel armor wires from the current cables.

However, a considerable amount of cost saving is expected if the armor material is made of stainless steel since this material is much more expensive than the Kevlar fiber we use to replace it. However, if we account other indirect costs such as project delay from cable failure, lost revenue for poor performance of the current cables, extra grease consumption at the stuffing box, loss of reputation by the client, and other issues, the expected benefit could be more than what we presented here.

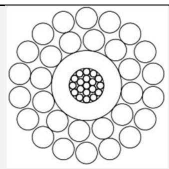
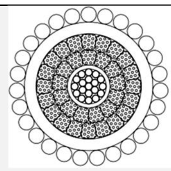
Overall, the cable under design concept II seems to have a marginal direct cost advantage if the armor wire is made of regular steel. Whereas, the design concept III is found to have a significant cost advantage if the armor is made of stainless steel. But, the cost estimation is not conducted based on actual consultation of manufacturers and significant deviation is unavoidable though the overall conclusion is expected to be unaffected.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary of the Findings

So far, we have been investigating the potential of Kevlar®49 fiber as strengthening unit of Monoconductor cables and also the two possible design approaches, design concept II and III. Among the two design approaches investigated, design approach III is found to be the best way of incorporating Kevlar®49 fiber and steel armor based on theoretical gains in leading performance indicators, improvement in breaking strength, weight reduction, and also based on results from the simulation software. Overall, typical improvements expected from the design change and also the likely unintended consequences of the proposed design approach is summarized as shown in table 5.1.

Table 5.1: *Summary of the findings - Camesa® Vs Concept Cable III©Yohannes/ UiS /AI*

No.	**Description of Key Performance Indictors**	 **Camesa /Reference**	 **Concept Cable III**
1.	Breaking strength (KN) • Regular steel based • Stainless steel based	 53.3 45.4	 66.3 62.9
2.	Cable weight , in air (kg/km) • Regular steel based • Stainless steel based	 288 294	 203.78 219.31
3.	Stretch coefficient (m/km/5KN) • Regular steel based • Stainless steel based	 1.35 1.80	 1.94 2.00
4.	Results from the Cerberus Simulation* • Demand on tractors (lbf) • Pulling force at the winch (lbf)	 879 6,300	 781 5,000
5.	Electrical Property -Addressing short circuiting problem -Electrical resistance of the armor(Ω/km) • Regular steel based • Stainless steel based	 - 6.9 36.7	 Excellent 18.92 18.75
6.	Estimated Cost, (USD/8.202km) • Regular steel based • Stainless steel based	 $ 38,250.00 $324,750.00	 $42,435.07 $165,323.29
7.	Expected Fatigue Life	-	Positive improvement
8.	Frictional wear life time	-	Slightly negative **
9.	Rotational stability/Torque balance	-	Negative effect
10.	Gas breakthrough & grease consumption	-	Positive Improvement
11.	Main change required at operation level	-	Modification of the cable head
12.	Maturity of the Inspection Method	Matured	Under Development
13.	Working temperature(long term /shot term)	< 260 ^{0}C/< 260 ^{0}C	< 177 ^{0}C / < 250^{0}C

Assessment based on regular steel armor(5/16" camesa - stainless steel version cable found weak and unfit to run for the well profile selected , hence comparison couldn't be made

**If the weight reduction outbalances the armor size reduction (negative effect), the net outcome could also be positive or unaltered (but the issue is recommended as further research topic)*

5.2. Conclusion

The specific strength (breaking strength to weight ratio) of the cable and the integrity of the copper conductors with the steel armor wires are found to be the main problems of the currently used 5/16" - monoconductor cables. Furthermore, corrosion resistance versions of the currently used cables are also known to be highly expensive despite their limited breaking strength and poor electrical property. In addressing these and other identified problems, I have proposed the idea of integrating high strength fibers (Kevlar ®49) with steel armor wire so as to reduce the weight of the cable, improve the useful working strength, alleviate electrical short circuiting related problems, enhance the fatigue life time , and other aspects of the cable.

In doing that, the mechanical, chemical, thermal, and electrical property of Kevlar®49 fiber was assessed based on literatures, scientific data, advancement in synthetic fiber and composite materials, and also current trends in cable and rope design. Based on this knowledge, a concept cable was proposed and investigated in detail and consultation with technical people at Altus Intervention (formerly called Aker Well Intervention). In broad terms, the new design approach is found capable of integrating the novel property of the fiber with the wear resistance of the steel armor, which the fiber primarily lacks. This in effect has created a cable which has a higher prospect of addressing most of the problems seen in the currently used cables.

In the design process, the difference in modulus of elasticity between the steel wire and the Kevlar®49 fibers was found a main cause of concern as the fiber is known to have a slightly higher elasticity than steel wires. However, it has been found possible to achieve the desired load distribution at the peak working load of the cable through the use of a smaller lay length (for the steel wires) than commonly used. Overall, the results found from the simulation software and the mathematical calculations indicate the exceptional potential of the new approach not only in alleviating the currently seen problems but also in creating additional safety margin and capacity to reach complicated wells.

5.3. Recommendation

Based on the positive results achieved from the preliminary investigation, I strongly recommend for development of a prototype cable and undertake all the necessary tests so as to review the tests results and compare them with the anticipated improvements. It is also my endorsement to incorporate the knowledge and experience of cable manufactures so as the concept could be even further streamlined and get the necessary approval from relevant authorities.

Moreover, the suitability of the currently available fiber rope inspection techniques to this concept cable also needs further study and I advise Altus Intervention and other stakeholders to pursue the case as the success of this cable also depend on the presence of a reliable inspection technique. The applicability of the concept towards other grades of wireline cables (both mechanical and electro-mechanical), and also the possibility of finding non-steel based abrasion resistance material to replace the entire armor wire is also sighted as possible research topics and worthy to trail down.

REFERENCES

AMERICAN BUREAU OF SHIPPING (2011) Guidance Notes on the Application of Fiber Rope for Offshore Mooring. [Online] Available from: http://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/90_FiberRope/GuidanceNotes. [Accessed: 4th May 2014].

BROWN, I. & BURGOYNE, C.(1999) The Friction and Wear of Kevlar 49 Sliding Against Aluminium at Low Velocity under High Contact Pressures, ELSEVIER, Wear 236(1999) 315 - 327.

BUNSELL, A. (2009) Handbook of Tensile Properties of Textile and Technical Fibers. Cambridge: Woodhead Publishing Limited.

BURGOYNE, C. (1992) Aramid fibres for civil engineering applications. Construction Materials Reference Book. Butterworth's: Malaysia.

BURGOYNE, C. (1993) Developments in the Use of Unbonded Parallel-Lay Ropes for Prestressing Concrete Structures. FIP 93 Symposium. Kyoto, Japan.

CAMESA.A WIRECO WORLDGROUP BRAND. (2013) Product Specification Catalogue. Rosenberg, USA

CCISCO (2014) Wire Rope Design and Construction. [online] Available from: http://www.hanessupply.com/content/pdfs/wireRope101.pdf. [Accessed: 1st June 2014].

CHANG, K. (2011) Aramid Fibers. E.l. Du Pont de Nemours & Company, Inc. [online] Available from: https://polycomp.mse.iastate.edu/files/2012/01/3-Aramid-Fibers.pdf. [Accessed: 17th April 2014].

CHRISTINE, D. (2014) Comparison of Carbon Fiber, Kevlar (Aramid) and E Glass used in Composites for Boatbuilding.[online] Available from: http://www.christinedemerchant.com/carbon-kevlar-glass-comparison.html. [Accessed: 23rd April 2014].

DUNNING, D. (2013) Frequently Asked Questions (Camesa). [online] Available from: http://www.camesainc.com/Resource_/TechnicalReference/2145/Camesa_FAQ_Dec2013.pdf. [Accessed: 22nd March 2014].

FAHEY, T. (1990) Nonlinear and Anisotropic Behaviour of High Performance Fibers. Massachusetts Institute of Technology, Massachusetts, USA.

FATZER SERVICE (2001) Wire Rope Technology.[Online] Available from : http://www.riggingspecialties.com/sites/default/files/Wire%20Rope%20Technology%20by%20Fatzer.pdf. [Accessed: 1st February 2014]

FLORY. J. & BURGOYNE, C. (1990) Length Effects Due to Yarn Variability in Parallel- Lay Ropes. [Online] Available from: http://www-civ.eng.cam.ac.uk/cjb/papers/cp15.pdf. [Accessed: 9th March 2014].

GENERAL CARGO SHIP (2010) Lay of Ropes and Hawsers Used on Board a General Cargo Vessel. [online] Available from: http://www.generalcargoship.com/lay-of-ropes.html. [Accessed: 14th May 2014].

GIBSON, T. (2001) Handbook of Oceanographic Winch, wire and cable Technology. 3rd Ed. [online] Available from: http://docs.niwa.co.nz/library/public/BasJoHand.pdf. [Accessed: 30th April 2014].

HEISLER, S. (1998) Wiley Engineer's Desk Reference: A concise Guide for the

Professional Engineer. 2nd Ed. Canada: John Wiley & Sons, Inc.

KEVLAR ARAMID® FIBER (2013) Technical Guide. [online] Available from: http://ebookbrowsee.net/kevlar-technical-guide-pdf-d49230582. [Accessed: 2nd June 2014].

KOORDENFABRIEK VAN HOUTE NV (2014) Synthetic and Natural Fibre Rope Catalogue. [online] Available from: http://www.exsil.be/. [Accessed: 11th February 2014].

MOFFATT, T. and MADDEN, T. (2012) Corrosive Environments and Wireline. Quality Wireline and Cable Inc. [online] Available from: http: //www.wellservicingmagazine.com/featured-articles/2012/11/corrosive-environments-and-wireline/.[Accesssed: 10th April 2014].

PARIMALA, H. AND VIJAYAN, K. (1993) Effect of Thermal Exposure on the Tensile Properties of Kevlar Fibres. Journal of Materials Science Letters. Vol.12.P.99 – 101

QUALITY WIRELINE AND CABLE Inc. (2010) A Historical Perspective on Drum Crush and some Basic Tips to Help Prevent It : Technical Bulletin One.[online] Available from: http://qualitywireline.com/TB1.pdf. [Accessed: 11th May 2014].

REBEL, G. (2012) Past, Present and Future of Wire Rope Technology and Development. 2012 CICA Conference. [online] Available from: http://www.nobles.com.au/Site-Images/CICA-2012-Documents/Past-Present-and-Future.aspx. [Accessed: 7th March 2014].

REBEL, G., VERREET, R. and BRIEM, U. (2005) Composite Steel Wire Ropes for Mine Hoisting Applications. Hoist and Haul Conference. Perth, Australia

SIMEON, W. (2001) High Strength Synthetic Fiber Ropes. [online] Available from: http://www.unols.org/…/03_synthetic_fiber_ropes.pdf. [Accessed:23rd May 2014]

TSAI, S. (1979) Composite Materials: Testing and Design. American Society for Testing Materials. Fifth Conference, New Orleans

VERREET, R. (1997) The Rotational Characteristics of Steel Wire Ropes. [online] Available from: http://www.fastlift.co.za/pdf/CASAR%20-%20Rotation%20characteristics%20of%20steel%20wire%20rope.pdf. [Accessed: 8th May 2014].

WIRELINE WROKS INC (2005) Technical Bulletin Number - 021. [online] Available from: http://www.sssg.whoi.edu/sssg/winch_wire/Tech-Bulletins.pdf. [Accessed] 29th March 2014.

YOUSSEF, H., EL-HOFY, H. & AHMED, M. (2011) Manufacturing Technology: Materials, Processes, and Equipment. CRC Press Inc.

APPENDICES

Appendix 1 – General Properties of Camesa 1N32 – 5/16" Monoconductor/Regular Steel

Properties	
Cable Diameter	8.18 mm + 0.13 mm - 0.05 mm
Minimum Sheave Diameter	46 cm
Cable Stretch Coefficient	1.35m/Km/5KN
Electrical	
Maximum Conductor Voltage	1,500 VDC
Conductor AWG Rating	15
Minimum Insulation Resistance	457 Mega Ω/Km @ 500 VDC
Armor Electrical Resistance	6.9 Ω / Km
Mechanical	
Cable Breaking Strength (Ends fixed)	53.3 KN Nominal
Maximum Suggested Working Tension	26.6 KN
Number and Size of Wires	
Inner Armor	12 x 1.130 mm
Outer Armor	18 x 1.130 mm
Average Wire Breaking Strength	
Inner Armor	1.97 KN
Outer Armor	1.97 KN

Cable Type	**Core Description**							**Cable Weight/Kg**	
	Temp Rating ^0C	**Plastic Type**	**Insulation Thickness mm**	**Copper Construction mm**	**Res Typical Ω/Km**	**Cap. Typical pf/m**	**O.D. Each mm**	**In Air**	**In H_2O**
1N32PP	149	Poly	1.067	19 x 0.361	9.2	151	3.937	278	230
1N32PXZ	216	Camtane ETFE	0.560 0.508	19 x 0.361	9.2	154	2.921 3.937	282	233
1N32PTZ	260	FEP ETFE	0.622 0.445	19 x 0.361	9.2	148	3.048 3.937	288	238
1N32WG	316	TE	1.067	19 x 0.361	10.5	151	3.937	290	240

Appendix 2 – General Properties of Camesa 1N32 S77, 5/16 ″ Monoconductor, Corrosion Resistant

Properties

Cable Diameter	8.18 mm + 0.13 mm - 0.05 mm
Minimum Sheave Diameter	46 cm
Cable Stretch Coefficient	1.8m/Km/5KN

Electrical

Maximum Conductor Voltage	1,500 VDC
Conductor AWG Rating	15
Minimum Insulation Resistance	457 Mega Ω/Km @ 500 VDC
Armor Electrical Resistance	36.7 Ω / Km

Mechanical

Cable Breaking Strength (Ends fixed)	45,4 KN Nominal
Maximum Suggested Working Tension	22.7 KN
Number and Size of Wires	
Inner Armor	12 x 1.130 mm
Outer Armor	18 x 1.130 mm
Average Wire Breaking Strength	
Inner Armor	1.66 KN
Outer Armor	1.66 KN

Cable Type	**Core Description**							**Cable Weight(Kg)**	
	Temp Rating ^{0}C	**Plastic Type**	**Insulation Thickness mm**	**Copper Construction mm**	**Res Typical Ω/Km**	**Cap. Typical pf/m**	**O.D. Each mm**	**In Air**	**In H_2O**
1N32WTZ-S77	See Below	FEP ETFE	0.622 0.444	19 x 0.361	10.5	148	3.048 3.937	294	243

Appendix 3 – Simulation Parameters - Design Concept III (Corrosion Resistance Version)

Cable Parameter – 5/16″ Stainless Steel Armor		
Cable Type		
Nominal Diameter	8.18 mm	0.322 in
Weight in Air	203.78 kg/km	0.137 lb/ft
Weight in Water	152.78 kg/km	0.103 lb/ft
Stretch Coefficient	2.00m/Km/5KN	1.78 ft/Kft/Klbs
Breaking Strength	62.90 KN	14,161 lbf
Max. Temperature Rating	160 ^{o}C	320 ^{o}F
Drum Crush Caution		
Drum Crush Warning		