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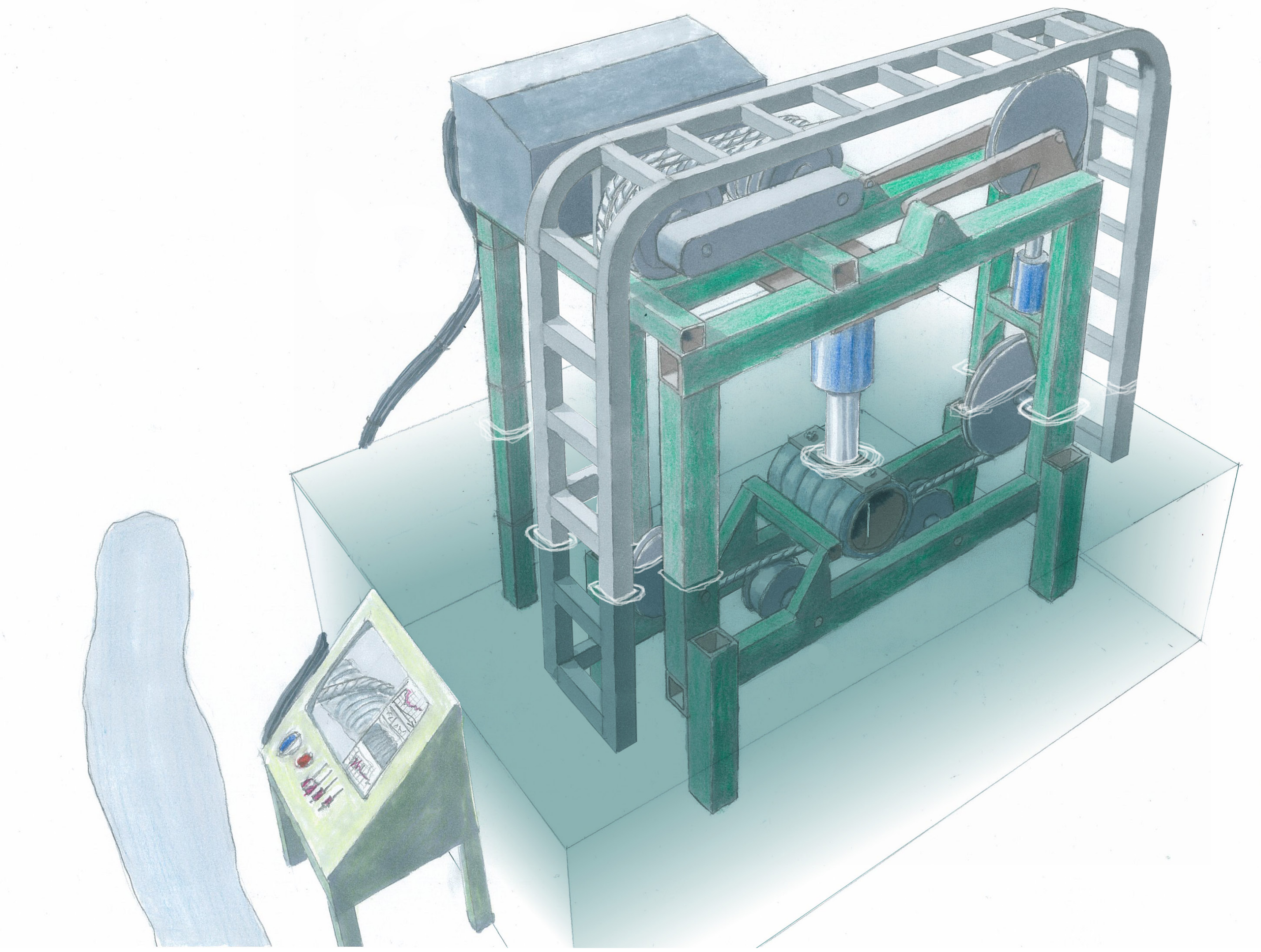

ABRASION TESTING USING WIRE

Development of a tribological test device for subsea applications

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Master thesis in Industrial Design Engineering
Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
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Cover:
Illustration of proposed concept of a wire abrasion test rig. Further information on page 42

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ABSTRACT

As offshore challenges increase, so must the level of innovation. The extraction of oil and natural gas from the bottom of the ocean has long been dependent on oil production facilities, which are moored to the bottom. However, catenary moorings have a limit of 450 meters depth. Thus evolved the use of polymer mooring line, enabling companies to extract previously unattainable oil. But with a new technology comes new challenges and a current problem experienced with polyester mooring lines is the damage caused by fishing gear such as trawlers and trawling wires.

The focus of this master thesis was the research behind and development of a testing device that is to make sure a cut-resistant jacket for offshore mooring lines can withstand an encounter with a trawler. The project was initiated by Calora Subsea, a Norwegian offshore company, with the intent of exploring the possibility for constructing scaled testing equipment to test the full-scale solution performance. The project is run with a central focus on Calora's solution for a cut-resistant jacket, Calorfloat, and much of test results and material science is centered around its specifics and material data.

This report describes the current situation of offshore equipment, formulated and motivated demands and specifics on testing equipment as well as the results of own experiments and interviews with people and organizations in the offshore industry.

Deliverables were originally a finished test rig and evaluation of its performance but, due to facts presented in the report, this changed to the conceptual proposal of a test rig, specifying functions and equipment needs in order to form a solid base for later construction of the device.

The process utilized within the project is an iterative product development process, based on a platform of knowledge gathered from literature, interviews and experiments and implemented through the planning, generation, development, conception, evaluation and enhancement of four different solutions. With the aid of thermodynamics and finite element analysis, the material's behavior is predicted and based on the theories developed through research and interviews on the scalability of thermodynamic abrasion tests, the design of a scaled rig for simulating the event of a trawler incident is proposed.

Though much work was laid into the design of the test rig, some questions remain to be answered through further work and is not answered in the thesis.

Keywords: Tribology, Abrasion, Testing, Steel cable

PREFACE

Welcome, dear reader, to the report of a Master thesis by a humble industrial design engineer destined for adventure, fame and glory. Such things aside, you picked up a tome of work that may or may not drown in other academic publications and, if you care enough to read it, inside you will find the documentation of half a year of work, featuring daring adventures among Norwegian fjords, arcane mystifying machinery and incomprehensible illustrations. And Legos. Far be it from me to diminish the value of standardized, motorized, functional and yet easy to get mock-up material. While its professional value may not be one of the more recognized, the value of a functional communication model for a concept is immeasurable. If not for the communication of solutions, functional approach and aid in making your thoughts take form, then for the faces of your fellow students when you cover your table in brightly colored bricks.

The summer of 2012 I spent working on my first project involving offshore technology. At Iden Produktionsutveckling we labored to calculate, simulate and predict the result of changes to extrusion dies for Calora Subsea's production of Calorflex®. The work was brain-wracking, but rewarding and in the end I was offered the chance to do my master thesis in cooperation with Calora. As can be deduced from the existence of this report, I took the job and set to work on the exciting task laid out before me. There were a lot of obstacles and challenges and since I have been working alone, motivation was not always on top. But in spite of hills and valleys in the rough terrain, there were always people there to cheer you up, encourage you and praise your work. Though I cannot mention them all, a lot of people deserve a featuring in the list of persons to thank. They are the everyday men and women, tirelessly trudging through life by your side. Thank you, all of you. And a special thanks also to the people who have contributed with knowledge, time and effort to my work:

Allan Boye Hansen, Calora Subsea
Stig Hurlen, Mörenot A/S
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Kjell Larssen and Björn Melve, Statoil
Göran Brännare, Applied Mechanics, Chalmers
Ulf Olofsson, Tribology, KTH
Poul Laubjerg, Laubjerg vinsch AB
Linda Rolfö, Opposition

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INTRODUCTION

This is the introduction of the thesis, where the background, aim and objectives of the project is described.

Calora Subsea is a Norwegian industrial company developing and supplying thermal insulation for offshore flexible pipes. They have been looking for other applications of their field of expertise and have developed a new, similar material which might work to increase the robustness of polyester mooring cables for floating oil production facilities in the North Sea. Traditional, all-chain catenary moorings approach the limit of their capability at a depth of about 450m, while combined chain and steel wire-rope systems remain effective to approximately twice this depth before the weight of the mooring begins to sag excessively, and performance and station keeping comes at risk. (Offshore technology (2009)) With Statoil's planned launch of the world's largest SPAR platform, Aasta Hansteen, which is to be deployed at 1300m depth, there is a clear opening for Calora to prove their worth to the oil industry of Norway. Provided that their material can be proven tough enough to withstand the stresses of the North Sea environment.

Fig 1. Ordinary steel wire cross section and the constitution of a polyester mooring cable (Gabrielsen (2012))

The main threat to polymer mooring lines is limited resistance to external damage, especially from trawl wire. When deep sea trawling, fishing ships regularly cross the area around oil rigs, intentionally or by accident. If passing over a mooring line with a trawl trailing deep enough, the steel cable connecting the trawl to the ship will be dragged over the mooring line until the trawl passes over it. The forces in such an encounter are large enough for the trawl wire to saw through the mooring line, see Figure 3 below.

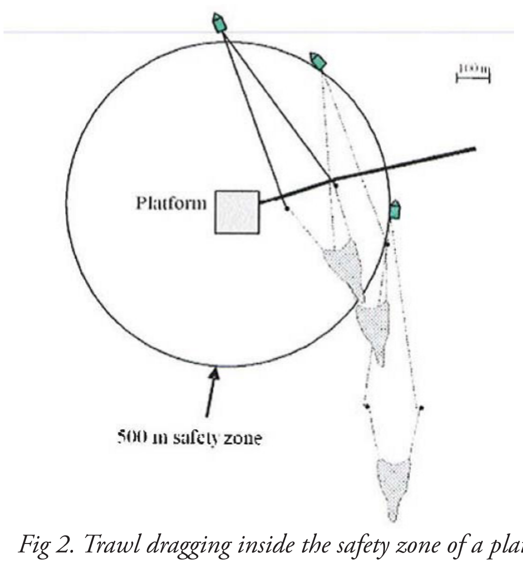

Fig 2. Trawl dragging inside the safety zone of a platform

Fig 3. Mooring line cut by trawl wire (Larsen (2011))

Thus, with the launch of Aasta Hansteen planned for 2016, Det Norske Veritas (DNV) has issued a mission for 44 subcontractors to develop a cut resistant protection for the mooring lines. With Statoil, they have also developed a set of testing specifications that the cut-resistant jacket must pass in order to prove its functionality. (See Appendix I) Calora Subsea, as one of the four remaining subcontractors, has come up with their solution to protect the polyester mooring line and their rigorous small and large scale testing shows that it can resist a trawl wire according to Statoil's test specifications. However, when DNV in cooperation with Statoil tested the same solution in full scale, Calora's protection did not pass the test. Statoil's testing, however, raised numerous question about the difference between the testing set-up and the actual operating conditions. This raises a number of questions regarding fundamental scientific properties, such as temperature, abrasion, water cooling and friction heat among others. This master thesis will deal with those issues, exploring, mapping and testing what happens between the trawl wire and the protective jacket. Since full scale testing is very expensive, a new set of models or scaled testing would be required to effectively describe what happens between the trawl wire and the protective layer.

Fig 4. Aasta Hansteen, compared to Oslo Rådhus. Image courtesy of Aker Solutions

AIM

This project aims to deliver a theoretical and a physical model that accurately describes the impact a trawl wire has on a cut-resistant jacket. In the theoretical case this should be a model based on calculations and theory of material science. The model should be flexible, comprehensible and trustworthy, enabling a user to view the theoretical result of a trawl wire impact under different circumstances within a normal variation span. The physical test should do more or less the same, but physically, actually pulling a length of wire over a sample cut-resistant jacket.

OBJECTIVES

- Develop a testing method, model or simulation that will comprehensively, scientifically and convincingly show whether a protective layer passes DNV's testing procedure or not.
- Develop a theoretical model which describes what happens during a trawling collision.

DELIMITATIONS

The main limitation for the project is that it will not go into the behavior of fishing and trawling patterns. These studies have been done before and are described thoroughly by Statoil. Thus, these specifications will not be further delved upon. The project will not go further into mooring line specifications, since the subject would be too large to include under the twenty week time limit of the master thesis. Instead, it will utilize practice developed by Calora Subsea in order to approximate the mooring line for physical testing. Although part of the original specification, the project will not deliver a finished prototype test rig, for reasons explained in the Further Development chapter. Nor will it deliver finished blueprints or part specifics, although the demands set for these will be presented.

BACKGROUND

Environment

The North Sea is famous for its harsh environment, making subsea installations and maintenance a hazardous task. The immense depths, massive waves and limited weather windows for marine operations create the need for equipment that will be easy to install and need little to no maintenance. Equipment for Aasta Hansteen, set in Luva which is 320 km west of Bodø, is designed for a significant wave height of 18 meters, compared to the 12 meters of the Atlantic Ocean. The design measurement is often called "The Hundred Year Storm", meaning that once in a hundred years, statistically, a storm of this magnitude will appear. (Skaugset (2009)) This means that equipment really needs to meet standards set five to ten times over what is actually necessary. There must be no failure, because the consequences are more often than not catastrophic, expensive and extremely hard to undo. It also sets requirements on the strength of a damaged mooring line. According to DNV, a cut-resistant protection should make sure the mooring line holds at least 40% of the original Minimum breaking strength (100% of MBS is 2000 tons) after a trawling incident.

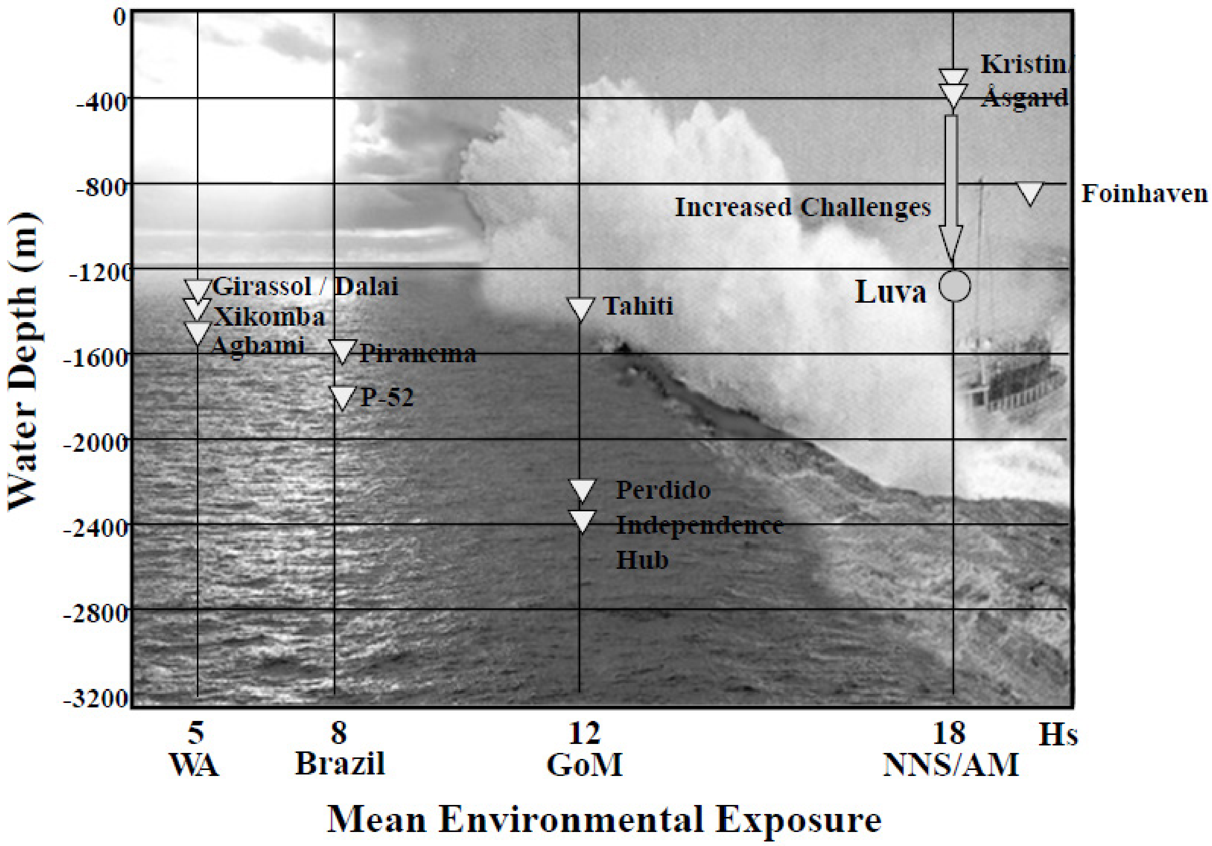

Fig 5. The significant wave height (meters) of different seas, such as the Wandel sea, Gulf of Mexico and Northern North Sea. Aasta Hansteen will be situated in Luva (Larsen (2011))

Similar applications and testing

Steel cable resistance testing is a narrow area, since most wire testing involves testing of the wire, not the material it runs over. (Certex Svenska AB (2013)) Usually, cable wires are tested for strength, toughness, use deformation and corrosion resistance. The stiffness increase of deformation may be important when constructing a testing rig, as the cable properties change during the test, affecting the result and eventually damaging the cable through fatigue if tight bends or loops are part of the construction. (Youdale (2012)) Further worth noticing is that a trawl wire will be replaced at the first sign of damage. This can include fatigue breaks, twisted chords or similar obstructions which may cause higher local strain on the material, which would increase wear. (Weischedel (2003), Hansen (2012)). The steel cable used in experiments and calculations can

thus be assumed to be without fault, evenly wound and periodic to the length of its beat, which simplifies assumptions, decreases friction work and makes test material easier to acquire.
Abrasion testing is however normal in most material design, including metals, ceramics, fabrics and plastics. This is usually done by applying a moving surface or object to a test piece. The abrasive object can be everything between rotating rubber wheels, scratching claws, pins, sand paper or similar objects.
The test should not be used to predict the exact resistance of a given material in a specific environment. (Element (2013)) Its value lies in predicting the ranking of materials in a relative order of merit as would occur in an abrasive environment. Furthermore, the current testing situation is too specific, the demands on the end result too real-life, for such a general characteristic testing. It may be relevant, though, if several different material compositions are to be compared to each other.

Another relevant field dealing with steel cable is the wire saw. A wire saw uses a diamond impregnated wire to saw through materials like concrete. A hole is drilled at the top and bottom of the cut and the wire threaded through, guided through a series of pulleys and connected to its other end, forming a loop. An engine starts the wire, which is pulled taut by moving the engine along a rail. The wire effectively saws its way through, creating a high quality cut. (McLaughlin (1989), Cutting Edge (2013)).

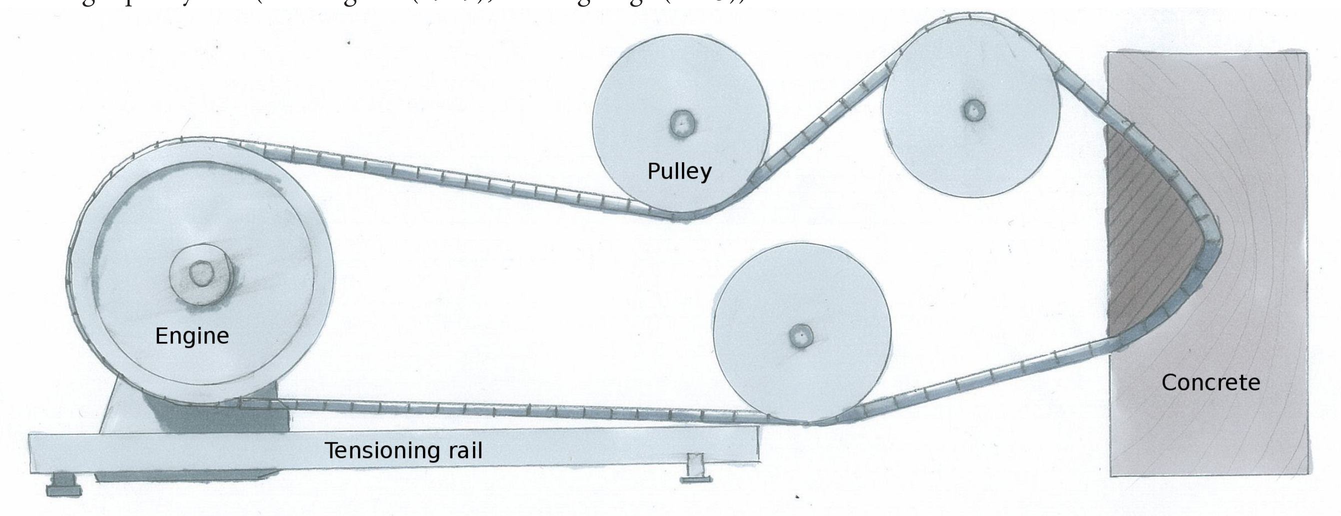

Fig 6. Schematic illustration of a wire saw

If a similar approach can be made with a prototype, or if a similar machine can be run with a trawl wire, a lot of design and thinking work may be saved. A concern, though, is the high contact force used to simulate the pull of a trawler, which the machine might not live up to.

Testing apparatus

Though rare, actual wire resistance testing apparatus do exist. Mörenot AS, another Norwegian offshore company, has one (See Figure 8 overleaf) which is primarily used for testing their own CRJ solution, the Dyneema jacket.
The basic principle of the Mörenot testing rig is to pull a section of wire back and forth over a sample to simulate the wear of a long wire. The wire is tensed with a weight, usually scrap metal and shackles. In the other end, the wire is connected to a 300 mm turn wheel, which when turning at constant speed makes the wire move back and forth in a sinusoidal manner, where the wire maximum speed is the wire speed given in the

Fig 7. Sliding marks on Calorfloat sample from the Mörenot test rig

tables 1, 2, 3 and 4 in the Project Approach section.

The sample is also cooled with fresh water from a garden hose, meaning there is plenty of medium to transport heat away from the sample, allowing it to remain below 10 degrees centigrade.
The sample is a 100 mm aluminum pipe with a Cut-Resistant Jacket (CRJ) sample fixed to it.

Since the wire is not traveling in a single direction, but back and forth, and is spun right handed, the wire slides to the left when going up and right when going down, moving the wire sideways with each period. After a while, the wire will settle in a groove and start cutting at the same place (See Figure 7 above).

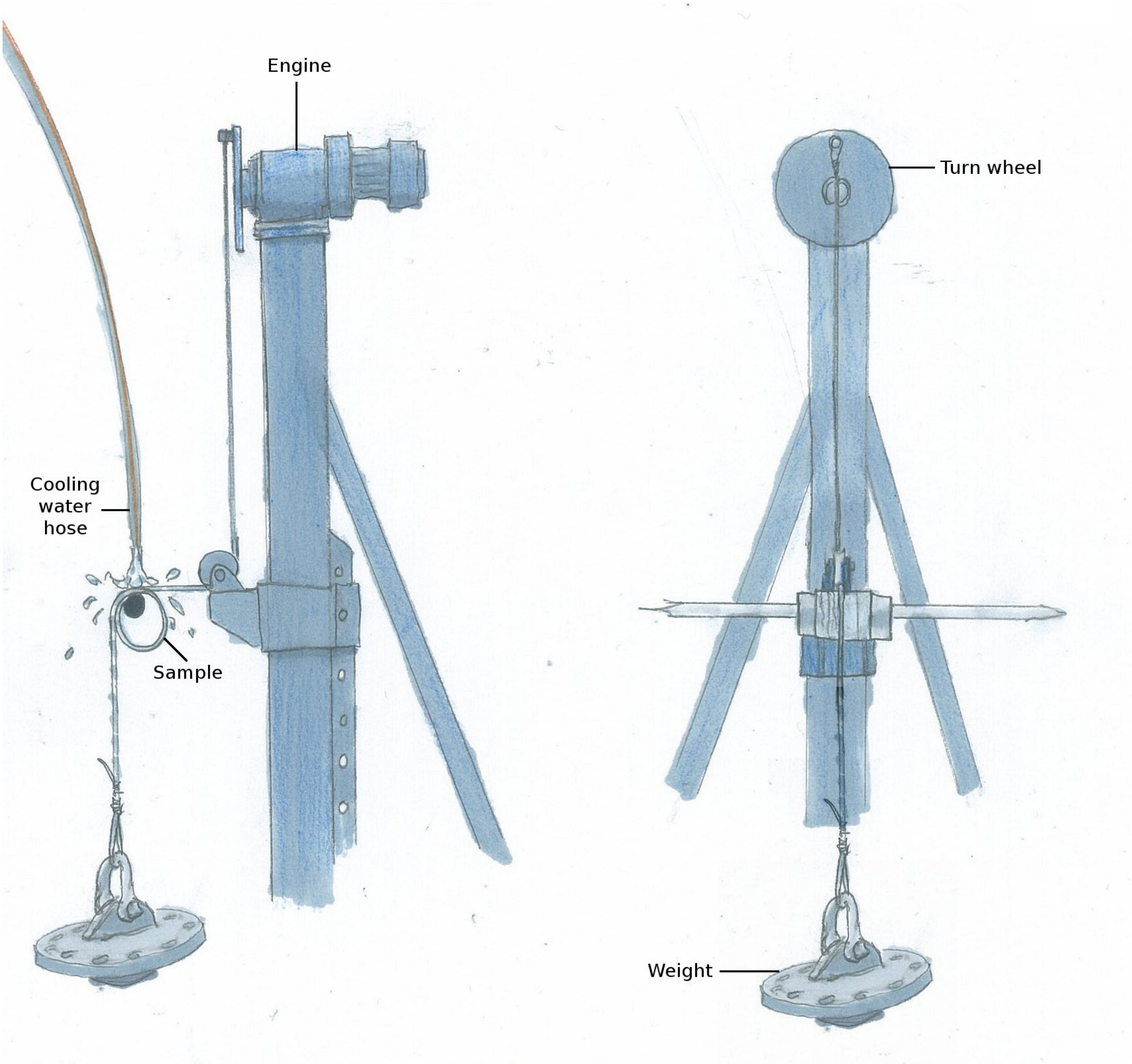

Fig 8. Schematic illustration of the Mörenot test rig

This complicates comparison between different samples, since the wire will begin cutting in the same place at different times. To counter this was defined the "slide width 0" criteria, which nominates after how many cycles the wire did not move sideways. This was to symbolize the time when the wire settled in a groove and started working on the same spot. From that point in time, all tests on this rig were run 165 cycles, regardless of when the 0-criteria manifested. By running it this way, the samples were supposed to be comparable afterward.

The maximum tensioning weight that can be supported is 150 kg, creating a tension of about 1.5 kN, a hundredth of the true load. With heavier weights, the movement of the wire would move the entire test rig on the floor, pulling it towards the sample, ruining the test and damaging the device.

PROJECT APPROACH

To get a thorough overview of the project, its entirety must be mapped, sorted and scheduled. This section deals with planning, methods used and material science that is useful to know when reviewing the implementation, result and discussion of the project.

PLANNING

Map it

Thought maps are a well-practiced form of organizing complex structures. In order to methodically map up the project parts, details, actions, limitations, stakeholders and other categories, the project is divided into branches and subcategories. Topics branch out depending on necessary depth. This maps all the known factors, making it possible for the organizer to divide each problem or topic into finer details, without losing the picture of the whole project. (Johannesson (2004)) This was used to structure the parts of the project for further planning. In this project was utilized a free online mind-managing software called mindmeister. (www.meindmeister.com)

Arrange it

To create a map of the dependency of each action, as well as filling in the blanks not visible in a mind map, all stages has been structured into a flow chart (See Appendix II), arranged chronologically. This will make evident where there are chronological or functional gaps in an action, allowing the user to fill in and further extend the detail level created in the first mind map.
This way each dependency will be visible at all times during the project and defining what has to be done next, or what needs to be done to complete or start a task, will be easy. A large, printed version, preferably wall mounted, will also allow for additions, should one task have to be changed or further elaborated on.
The flow chart is also a necessary step for creating a schedule and time frame for the project parts.

Schedule it

Time frame: 2013-01-21 – 2013-06-04
To constrain each action in time, a Gantt schedule (See Appendix III) has been made, based on the features of the flow chart and mind map. With a comprehensible view of the entire project, start and end times, rough estimations of how much time each task takes will create a comprehensive chart for synchronizing the plan with the actual project progress. Time schedules, such as the Gantt schedule, allow an overview that shows not only when a task must be started in order for it to be completed, but also when a task must be ended, unless it is to delay the entire project. With a time constraint on each task, the risk for overworking or getting stuck doing the same thing decreases. (Johannesson (2004))

The plan for real-life testing

The result of the project relied much on whether or not a prototype was to actually be built. This in turn relied on how quickly the plans for a reliable, believable and realizable solution could be produced.
Since the purpose of the testing rig is at this stage was yet to be fully defined, and maybe even researched, a good start was to define it.
With that in mind, a set of requirements for it was to be made and weighted in order to grade how important

the demand is. With specifications made the ideation phase could start. Based on how ideas fell out, concepts would be constructed from idea parts, solutions or reiterations. A few selected ones would be visualized and evaluated through mock-ups, function models, peer review and expert evaluations. Mock-ups would be easily be constructed in polyurethane, tape, strings, toothpicks and lots of glue, while function models was to be made from Lego. Once a concept had been established and gone through the preset requirements it was to be made ready for manufacturing. Parts, cost, requirements and specifications was established and the concept would be, if necessary, redesigned in order to ease construction.

METHODS

Literary research and peer review

The databases of the world are not exactly brimming with information on the very specific case of trawl wire abrasion resistance. There are, however, a good load of mechanical models for theoretical calculations on both thermodynamic and mechanical abrasion through course literature and engineering databases which can be combined to produce an approximation of the situation. Chalmers also has an extensive supply of professors and researchers and some were consulted on mechanical suggestions and review of concepts and ideas.
Literature consulted in this thesis is mainly thermodynamic and mechanical handbooks, product catalogs and manuals regarding equipment. A lot of information was also gathered through presentations by, interviews and meetings with key persons in Statoil, Den Norske Veritas, Mörenot A/S and Calora Subsea

Simulation

The quest for a cost-effective, efficient and reliable prediction of the real-life event of a trawler incident naturally progressed into the development of mathematical models to describe the event. If the result of the event can be predicted without even touching a steel cable, significant resources can be saved, which is why computer aided simulation has become a big part of product and process development industrially today. (Johannesson (2004))

Finite element analysis is a mathematical and numerical method that approximates a solution for a very complex set of simple calculations. This set of calculation often describes differential equations of great complexity, so complex that they cannot be solved through ordinary means. Ordinarily, this kind of problems are found in thermal, structural and mechanical calculations, but also in fluid flow and electrical efficiency. The applications are many and versatile.
The method principle seems simple; describe a problem through a computer generated geometrical model and theoretical physics. Divide the problem into many, many small parts and set each part's relation to the next, stating start values and boundary conditions. Then solve, compare errors between the solved problems, adjust values and solve again. This iterative calculation goes on, decreasing the error until it stops at a specific tolerance or when no solution can be found that matches all nodes. However, very thorough understanding of the problem at hand is required in order to correctly formulate and define all boundary and initial conditions. (Johannesson (2004))
The monstrous amount of linear differential calculations required is very well suited for computers and the number of FEM software companies on the market today reflects its popularity. The number of nodes in the model dictate how finely tuned the theoretical model is to the intended shape. Increasing the number of nodes will make the geometry more accurate, but also means more calculations and longer time before it is completed. In essence, think of it as Lego bricks. With a few bricks you can make the shape of a dog. It may be recognizable, but may very well be a horse too. By increasing the amount of bricks you use to construct the dog, you may find it easier to approximate the organic shape of man's best friend until you have a pretty good shape. But it will take so much longer time to build and require so much more bricks. In the same way, the FEM-analysis gets more accurate the more nodes are used but will take exponentially longer time with finer tolerances. (Johannesson (2004), Nilsson (2011))
What is most important to remember is that the simulation will give a calculation result describing how the underlying model reacts to fictional forces, not how the real life situation reacts. (Johannesson (2004))
In this project, the fluid, structural mechanic and thermal simulation program COMSOL was used.

Kesselring method

The Kesselring method is an evaluation tool made for concept comparison and selection. Each concept is individually graded according to a number of preselected criteria. Each criteria is weighted from 1 to 3 and this is then multiplied with how well the concept fulfills the criteria. The total sum is added together and the concept with the highest total score is the most valuable one, according to the preset criteria. (Johannesson (2004))

Visualization

As a visualization medium, paper and pens were used in this project. This allowed for quick and easy documentations and descriptions of ideas, forces, systems or similar. While a quick and cheap method of visualization, compared to digital sketching, mock-up building or computer-aided design, the final level of illustration quality is significantly lower than other methods, depending on the skill of the illustrator. It still communicates function and concepts to greater extent than verbal description. (Ulrich (2008))

Mock-ups

In order to create a foundation for describing ideas, concepts and functions during interviews and peer review, illustrations were complimented with functional models or mock-ups when the illustrated object was too complex to correctly communicate its function on paper. With the correct medium, functions of lesser complexity (such as size, weight, hydraulics, color or simple motor functions) can be illustrated through the model. This may be dangerous, though, since the concept may be perceived as complete and its performance presumed that of the final product. (Ulrich (2008))

Qualitative Evaluations

During the project, peers, professionals and experts were frequently consulted on concepts, solutions and recommendations. Not only can these supply evaluation of ideas and theories but also give valuable input and ideas to take the project further. (Ulrich (2008))These opinions were gathered mainly for concept evaluation in order to produce an extensive prediction of each concept's realized performance.

MATERIAL SCIENCE

Polymer tribology

Polymers flow readily even at low temperatures and pressures. Thus, they are generally used in environments with low load, speed and temperatures, compared to f.ex. ceramics or metals. The contact temperature in an abrasive situation between a surface and a polymer is a function of normal pressure multiplied by sliding velocity (PV). Thus, polymers are classified by their dry sliding PV limit. Beyond the PV-limit, the polymer will start to melt, or lose enough structural integrity to be easily removed by an abrasive force. This means the wear rate increases rapidly with temperature.

Normally, many plastics sliding against hard surfaces such as metals result in the formation of a thin plastic film on the metal surface. This decreases the wear on plastic further down the sliding distance, even as early as after a single mm, and will cause a lower coefficient of friction since the plastic film works as a lubricant for the contact surface. The coefficient of friction also generally decreases with increasing normal forces, since the asperities of the surface are totally deformed by high enough forces, causing the contact area to deform into what can be described as a single large asperity. (Bhushan (2002)) See Figures 9 and 10 for further reference.

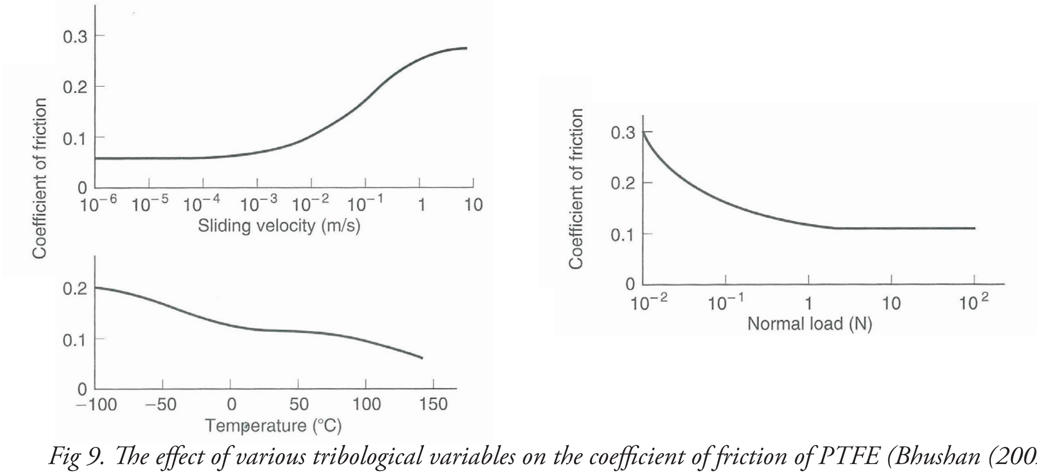

Fig 9. The effect of various tribological variables on the coefficient of friction of PTFE (Bhushan (2002))

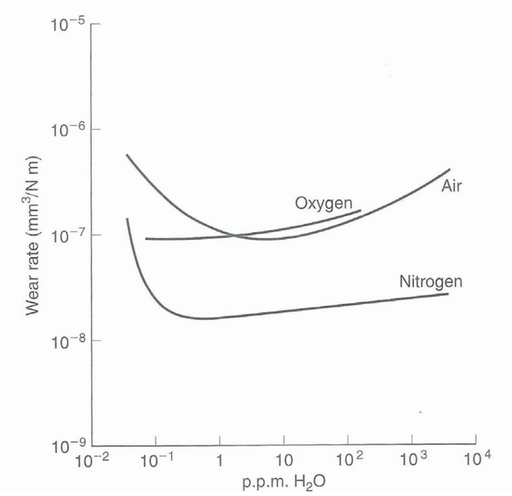

Fig 10. Wear rate of PTFE composite sliding against cast iron at 70°C as a function of water concentration in three different environments (Bhushan (2002))

If submerged, a polymer will generally absorb fluid. This degenerates mechanical properties, making the polymer less resistant to abrasion and wear. Since the cut-resistant jacket will be submerged during its working life, it is important that all test samples are thoroughly soaked for several hours before testing. On the positive side, water acts as a lubricant and a coolant, decreasing the increase in temperature induced by the sliding steel cable, thus allowing the plastic to work under high PV-conditions.
(Bhushan (2002), Sukuman et al (2012))
Water lubrication has advantages and disadvantages when it comes to polymer abrasion, derived from the involved mechanism and wear mode. Water lubrication in polymers-metal contacts can act as a cooling agent to reduce the frictional heating thus hindering heat build-up triggered phenomena like the softening, melting and transitions of polymers. Absorption leads to changes in structure at the surface level by swelling and also changes the tensile strength, which in turn alters the friction and wear behavior. Water absorption of polymers and plasticization are the two most common phenomena occurring in a water lubrication.
On the other hand, the positive effect of wet sliding is reduction of the induced shear stress and the total effect of submersion is determined by the characteristics of the material. This, however positive or negative, is determined by the dominating mechanism involved in the sliding process. The reduction in shear stress and cooling effect influences positive wear characteristics. The liquid absorption characteristics and the lubricant's removal of the transfer layer control the negative ones that decrease wear resistance.
Polyimide composites have also in testing produced better friction and wear behavior with water lubrication on comparing with dry sliding. The measured wear rate in water lubricated conditions was ten times less than in dry sliding. (Sukuman et al (2012))

Calorfloat characteristics

Calorfloat is a material based on a thermoplastic. While its composition and material characteristics are confidential, courtesy of Calora Subsea, it has much of the same characteristics as similar thermoplastic polymers. Its PV-tolerance in sliding conditions is not currently known, but facts such as specific heat capacity, friction coefficient against steel, melt viscosity, tensile modulus at different temperatures, melting point, glass-transition temperature and others are measured. Figure 11 shows the stress-strain relationship of a sample of Calorfloat at three different temperatures.

Though exact specifics are not available for display here, it is clear that Calorfloat loses structural integrity as it warms up. Between 5 and 50 degrees, glass transition occurs and it is probable that at this point the material will have lost enough of its solid durability. If put under stress, the warmer Calorfloat is much more likely to lose shape and deform and this is going to be very important for the future development of the test rig. For if Calorfloat heats up enough during the event of a trawler collision, it will start deforming rapidly. But if its temperature can remain below glass transition, it will prove a much tougher cut-resistant jacket.

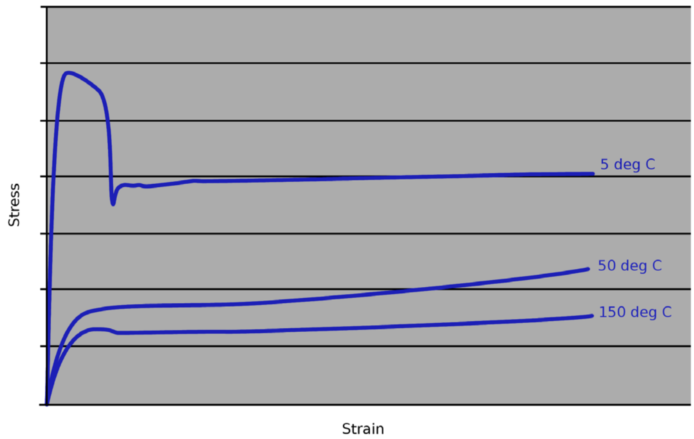

Fig 11. Stress-strain curves of Calorfloat at different temperatures

Scalability

Scaling the test is very desirable, since this lowers costs, makes rapid prototyping possible and decreases encumbrance for the company.
The scalability of the experiment is subject to how the differentials of thermodynamics change with size. Additionally, in order to produce the same material phenomena in a scaled version, contact pressure and wire velocity must be held constant. They must not change with the scale of the test. (Bhushan (2002), Olofsson (2013)).

"If a downscaling of the experiment is to be successful, you will have to verify that it is the right mechanisms of deformation working, regardless of full-scale or downscaled trial. To succeed with a down-scaling you'll need to pay attention to contact pressure, contact temperature and sliding velocity among others remain the same for a downscaled test as for a full scale one." - Ulf Olofsson, Professor of Tribology, KTH, 12/2-13 (translated from Swedish)

This provides a base of restrictions for a theoretical scaling of the test. Since contact pressure follows:

$$p=\frac{F}{A}$$

and the force is to be scaled down to simplify the test, the area must decrease with the same linear scale as the force. Assume the contact area projection in the direction of the contact force is a rectangle which width is the diameter of the steel wire and length is the indention in the sample, dependent on the radius of the sample. Keeping either constant and scaling the other would accomplish the goal and since the sample is affected by thermal conductivity and is harder to scale than the wire, assume the wire diameter is scaled as much as the contact force.

The wire speed must also be kept constant, regardless of the size of the wire. This means an equal distance of wire must pass over the sample, for heat build up to resemble the full scale test. This will affect the Work done by the steel wire on the sample. The definition of friction Work:

$$W=F_k*\mu*s$$

The work is equal to the friction force (contact force times coefficient of friction) times distance traveled. This results in a work that will be cubically scaled, thus if the test is scaled by a factor X, the work done will be X times as little. This also means the heat build-up will melt X times as little material. However, due to the decreased area of contact, the wire will also have X times less material to melt and the convective cooling rate will also decrease by a factor X. This means that although the work is decreased, the heat flux and depth of melting remains the same. Since the sample size remains unchanged, its heat convection ability should also remain unaffected, due to the constant heat flux from the contact area.

$$Speed, v = 2m/s$$
$$Contact\ force, F_k = 46000\ N$$
$$Wire\ diameter, d = 0.028\ m$$
$$Length\ of\ contact, l = 0.1\ m$$
$$Wire\ length, s = 600\ m$$
$$Contact\ time, t = \frac{s}{v} = 300\ s$$
$$Coefficient of\ friction, \mu = 0.14$$
$$Specific heat\ capacity, C_p$$
$$Tension, T = 147000\ N$$
$$Density, \rho = 1115\ kg/m^3$$
$$Convective\ cooling\ coefficient, h = -20\ W/m^2$$
$$Assumed\ temperature\ change, \Delta T = 110^o K$$

$$Linear\ scale\ factor: 4$$

Original scale

$$Contact\ pressure: p = \frac{F}{A} = \frac{F_k}{d*l} = 1{,}64\ MPa$$
$$Friction work: W = F*s = F_k*\mu*s = 3864000\ J$$
$$Material melted: m = \frac{W}{C_p*\Delta T} = 14.051\ kg$$
$$Depth\ of\ melting: depth = \frac{V_{melted}}{A_{contact}} = \frac{\frac{m}{\rho}}{d*l} = 4.5\ m$$
Convective cooling:
$$q = h*A_{contact}*T = -20*d*l*T = -22.288\ J/s$$
$$Heat\ flux: \overset{o}{q} = \frac{\overset{o}{W}}{A_{contact}} = \frac{\frac{W}{t}}{d*l} = 4.6\ MW/m^2$$

Scaled by 4

$$Contact\ pressure: p = \frac{F}{A} = \frac{F_k/4}{(d/4)*l} = 1{,}64\ MPa$$
$$Friction work: W = F*s = \frac{F_k*\mu*s}{4} = 966000\ J$$
$$Material melted: m = \frac{W}{C_p*\Delta T} = 3.5127\ kg$$
$$Depth\ of\ melting: depth = \frac{V_{melted}}{A_{contact}} = \frac{\frac{m}{\rho}}{d*l} = 4.5\ m$$
Convective cooling:
$$q = h*A_{contact}*T = -20*d/4*l*T = -5.572\ J/s$$
$$Heat\ flux: \overset{o}{q} = \frac{\overset{o}{W}}{A_{contact}} = \frac{\frac{W}{t}}{(d/4)*l} = 4.6\ MW/m^2$$

This assumes the contact force, F_k, will not reach the order of magnitude where it plastically deforms the sample and that the material is homogeneous, thus not on a structural basis affected by scale change (i.e. This would not work for a fiber-reinforced composite). It also assumes the texture of the wire does not affect the amount of abrasion the wire performs. This assumption is based on the polymer being removed by the wire as soon as it reaches glass transition temperature, thus softening enough to be easily and instantly removed.

If this argument holds true, a down-scaled test is not only possible, but yields the same depth of melting as a large scale test would. It would thus be possible to predict how much indention a wire would make in a cut-resistant jacked without performing a full scale test.

Based on the above calculations, a scaled test of a sample may prove useful in two applications. They can be used to predict the result of a full scale test, given that the material is homogeneous and the contact force remains in the elastic stress region of the stress-strain curve, and for material configuration comparison, given the same condition for all test samples.

THEORY VERIFICATION

In order to test the above theories and material phenomena, a study visit to Mörenot A/S, Sövik, Norway, was conducted.

This part summarizes observed test results and material behavior during a study visit to Mörenot A/S, Sövik, Norway. The testing was performed to assert the importance and relevance of several material phenomena, earlier observed by others (e.g. Bhushan (2002)), to the development of a test rig that is to simulate the situation where a steel cable is drawn over a cut-resistant jacket.

This was also an opportunity to study existing test rigs and to assess how well scaling of abrasion tests correlate to theory and hypothesis, asserting the importance of environmental aspects such as cooling and soaking of a polymer sample.

Plan for testing procedure and hypotheses

There were mainly two things that could be tested in the testing rig which mattered for this project. The scalability, which had thus far only been hypothesized, and what effect fluid absorption has on Calorfloat, thus elaborating on the theoretical wear rate change of this material in particular.

Scalability

By using different diameter of wire and a matching set of weights, the contact pressure and sliding velocity is kept constant in three different cases of different wires. The wires would have the same composition of material and structure, thus each wire representing a scaled version of the other. Hypothesis is that with they will cut to the same depth. If all three tests come up with the same cutting depth, the scalability hypothesis will hold true, meaning a scaled rig can be used to predict the effect of a full-scale test or, more importantly, the true situation.

Fluid absorption

Bhushan (2002) claims that wear rate changes if a polymer is allowed to absorb liquid. Both in that the coefficient of friction changes and the structural integrity of the polymer breaking up because of the fluid absorption. In order to test this, a sample of Calorfloat was allowed to soak in a bucket of water for 20 hours and was then subjected to the same testing procedure as one of the scalability tests, allowing a comparison between the two. Hypothesis was that wear rate would increase, though friction would be reduced.

Dry testing

In order to provide the other side of the cooling effect, a completely dry sample was also run. This happened with no cooling whatsoever, leaving the wire free to raise temperature in the test sample, possibly melting it. This was also done with the same specifics as the fluid absorption and scalability tests, with the exception of cooling, to provide comparison between the situations. An additional test, with double speed, was also run on the premises that increased speed would bring the material closer to its PV-limit. Hypothesis is that without cooling, the material will melt and wear rate increase, causing a deeper cut.

Experiments

For description of the Mörenot test rig, see Testing apparatus, page 5.

Scalability testing

Three sizes of wire and weights were run, see table 1 below. Each size of wire was tensioned with approximately 28,6 kg/mm diameter as this makes the 5 mm wire test run with the maximum weight the machine can tolerate. The tests were run, one at the time, starting with 3 mm, switching to 1.5 mm and then 5 mm. The samples were studied and the cutting depth measures with a caliper.

Table 1 – Scalability testing data

Sample	1,5 (A)	3 (B)	5 (C)
Wire dimension	1,51 mm	3,1 mm	5,2 mm
Wire speed	200 cm/min	200 cm/min	200 cm/min
Tension weight	43,2 kg	88,44 kg	141,4 kg
Cycles	250 rot	200 rot	240 rot
Slide width 0 at	90 rot	35 rot	85 rot
Cooling	Full	Full	Full
Cutting depth	0,41 mm	0,86 mm	0,94 mm

Fig 12. Profile view of 1.51 mm, 3.1 mm and 5.2 mm Calorfloat samples

Fig 13. 1,51 mm sample

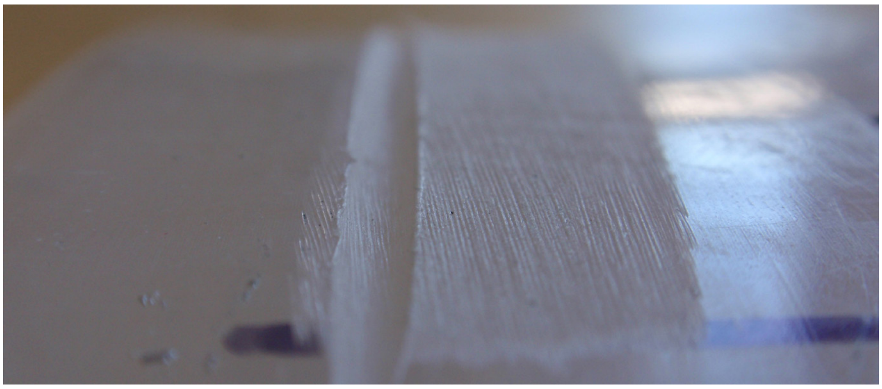

Fig 14. 3,1 mm sample

Fig 15. 5,2 mm sample

As is evident from the cutting depth of the wires, the scalability hypothesis cannot be proven true or false, since there are different cutting depths displayed where they should be same. On the other hand, both the 3 mm and 5 mm wires (Figures 14 and 15 respectively) cut to roughly the same depth and due to time limitations, the tests could only be run in a single iteration. So the results from each test may or may not be entirely reliable, depending on how much variation one can expect from the testing rig.

Soaked and dry testing
In order to try out the effects of cooling and soaking, three more tests were run. One where the sample had been soaked in a bucket of water for 20 hours (overnight) and two without cooling but at different wire speeds (See table 2). The other parameters were set the same as the 3 mm wire of the scalability test in order to provide comparable data. See table 2 below and image 6 to 9 for results. The second dry test was run to see what happened if the PV-condition was increased for the sample. Since the pressure could not be increased, due to weight limitation, the speed was.

Table 2 – Soaked and dry testing data

Sample	Soaked (S)	Dry (D)	Dry II (-)
Wire dimension	3,1 mm	3,1 mm	3,1 mm
Wire speed	200 cm/min	200 cm/min	400 cm/min
Tension weight	88,44 kg	88,44kg	88,44kg
Cycles	230 rot	300 rot	300 rot
Slide width 0 at	65 rot	85 rot	-
Cooling	Full	None	None

Fig 16. Profile view of Soaked and Dry Calorfloat samples

Fig 17. Soaked sample wear

The wear on the soaked test sample was about the same as the corresponding scalability test. This may be because of the tendency of increased wear rate of polymers that have absorbed liquid. The liquid causes a structure mechanical breakdown in polymers, decreasing the coefficient of friction somewhat, but also increasing wear rate (Bhushan (2002)). This is, however, highly dependent on the amount of water the polymer absorbs, which is very little in the case of Calorfloat. (Hansen (2013))
Slide width 0 appeared later in the soaked case, but this can be attributed to chance, slicker surface or uneven test pieces. Otherwise it would indicate a lower coefficient of friction in the soaked case.

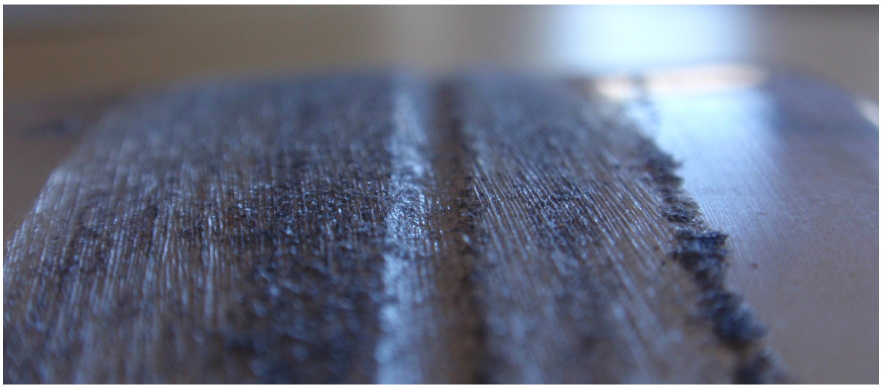

Fig 18. Dry sample wear. Notice blackened wear particles

The dry testing, however, showed a new set of material phenomena. The sample blackened, started melting and smoke was observed during the beginning of the test. Pieces of melted, blackened Calorfloat stuck to the sample surface and the wire (See Figure 18 and 19), which was pulled back into the cut area by the see-saw motion of the wire. The cut from the first test appeared late, but did, surprisingly, not go as deep as the cooled ones did. When set to double speed, the second Dry test, the test ran for 300 cycles without showing any signs of entering slide width 0. The test was stopped and no further data was collected, since the wire never cut at one place, but slid back and forth across the surface.

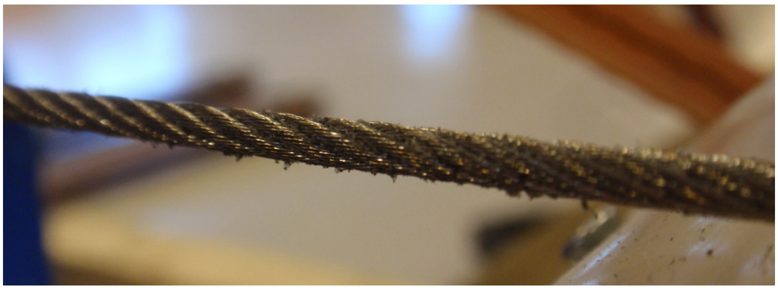

Fig 19. Wire with bits of molten Calorfloat during Dry testing

Dyneema testing

In order to compare with another cut-resistant-jacket solution, an additional test was run. The Calorfloat sample was exchanged for a braided Ultra High Molecular Weight Poly Ethylene (UHMWPE) jacket, the Dyneema jacket, which is a recognized product on the current market of protective jackets. It was run with the same speed, wire, weights and cooling as the 3 mm scalability test above (Compare to table 2).

Table 3 – Dyneema testing data

Wire dimension	3,1 mm
Wire speed	200 cm/min
Tension weight	88,44 kg
Cycles	165 rot
Slide width 0 at	0 rot
Cooling	Full
Cutting depth	Half (3-4 mm, see below)

Since the Dyneema coat is porous and fibrous, it is impossible to get a read of a cutting depth. Instead, the amount of cut fibers was counted and an estimation of cutting depth made. The wire had cut through half the jacket in the same number of cycles it cut 0.86 mm into the Calorfloat. Figure 20 shows that the fibers in the Dyneema jacket are approximately 3-4 mm thick, compared to the 3 mm steel wire. The cutting depth of the test would thus be approximately 3-4 mm, but since the fibers are compressible, this should not be taken as a fix value.

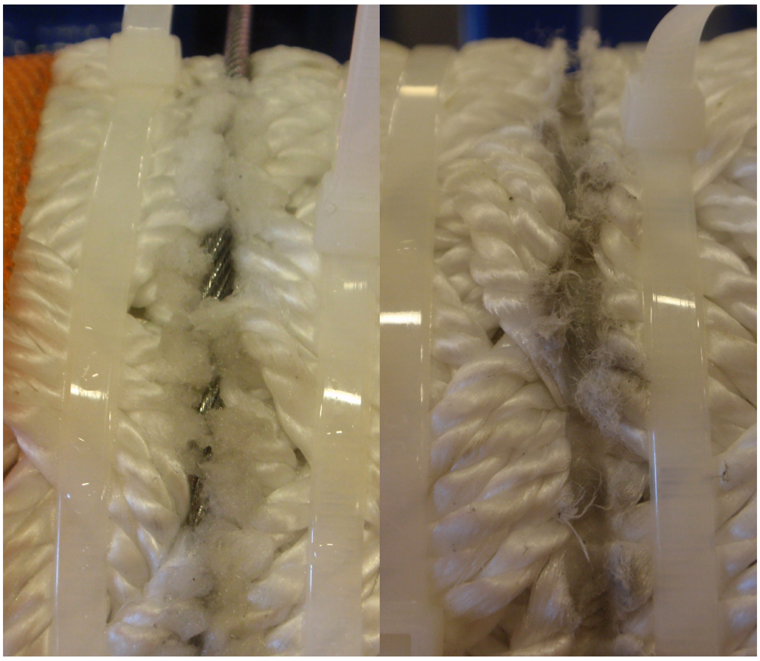

Fig 20. Dyneema test results, with and without wire in place

The slide width 0, as shown in the table above, was 0 rotations. The Dyneema coat is soft enough for the wire to nest itself in the fibers without sliding back and forth. This means that the wire started cutting immediately, doing abrasive wear for the first rotation.

Results, discussion and analysis of experiments

Scalability

The hypothesis of scalability can neither be discarded nor confirmed from these tests alone, since the results both point towards the possibility of it being true and being false. The 3 and 5 mm wires cut to roughly the same depth, indicating success, but the 1.5 mm wire cut only a fraction of the others, indicating dismissal. Through more, longer and harder testing this could be verified but in the limited time frame that these tests were done, it was not possible. Another test should include longer wear after slide width 0, in order to get a better comparison between wear rates, and more tension in the wire, inducing a higher PV-value.

Soaking

The effect of soaking the sample was negligible. If the Calorfloat indeed took up fluid and had its mechanical properties worsened, it did not have a huge impact on the result. This may be due to lessened friction compensated for higher wear rate, or it may be an insignificant difference due to low water absorption.

Dry

The dry result was an entirely different test when compared to the result from those with cooling. Temperature rose, the material melted and perhaps even burnt in the beginning. The cut made, though, was not as deep as either of the same-size wet tests. This might be due to material clinging to the sawing wire or molten material providing a liquid microfilm, reducing wear and friction. Since the same part of the wire, roughly 300 mm, is the part doing all the wear, alteration to its surface structure would have a great impact on the test result.

Comparison between Dyneema and Calorfloat

While the Dyneema coat wasn't cut through by the wire, it could not withstand the wire the same way the Calorfloat did. Both the abrasive wear and the slide width speaks to the Calorfloat's advantage, see table 4 below. A trawl wire will certainly not remain in the same place during a contact situation, but a porous fiber jacket is more likely to induce sliding wear on a single location compared to a smooth hard wrapped polymer cover, due to the surface hardness and slickness.

Table 4 - Collected comparable test results and data

Sample	Calorfloat 3 mm	Soaked CF 3 mm	Dry CF 3 mm	Dyneema 3 mm
Sample	3 (B)	Soaked (S)	Dry (D)	Dyneema
Cooling	Full	Full	None	Full
Slide width 0 at	35 rot	65 rot	85 rot	0 rot
Cutting depth	0,86 mm	0.83 mm	0,41 mm	Half (3-4 mm)

Error sources discussion

PV-limit

The PV limit of a polymer is a function of the maximum pressure and contact speed under which the polymer can be expected to function as intended. The PV limit of Calorfloat is not known, but the characteristics of the Mörenot testing device can at least tell something. The wheel and wire of the test rig moves at maximum 200 cm/minute. This provides a wire speed that is 60 times less than the current demands set by Statoil for tests, something which must be considered when viewing the tests. The contact pressure in the tests was also low compared to a real impact between a trawling wire and a sample. The tension provided by the Mörenot test rig was about 300 N per mm diameter of the wire, compared to the 5000 of the situation described in Statoil test instructions. A 3 mm wire should thus have a tension weight of close to 1500 kg, compared to the 88 kg that were used. Combined, this gives a PV-situation about 1000 times lower than what Statoil has set up as a requirement.

It is very probable that the Calorfloat was never near its PV-tolerance and that the wear seen on the samples are only the abrasive wear and none of the thermal (melting) wear. Further testing would probably yield more relevant results with a higher PV-situation.

Slide width 0

A certain source of error, the slide width parameter is not among the exact scientific specifications. It could at best be pinpointed to within 5 rotation of it happening, and then wear at the measure point had already in some way been started. But the parameter was necessary, since the to-and-fro wear before the wire settled needed to be filtered out of the number of cycles run, for the tests to be comparable.

Sawing

Furthermore, the wire was sawing, meaning whatever material was transferred from the sample to the wire would enter the cut again and again, something which does not occur in reality, where a long wire is pulled in one direction. This may be a source of error, since polymer adhesive transfer between the sample and the wire may alter the coefficient of friction as per Bhushan's (2002) descriptions. Especially in the dry condition, where the only source of lubrication was the molten material. This is significant and the change was observed in that the sample was emitting smoke at the start of the test, but stopped after a few rotations. The material may have adhered to the wire, lowering the friction and the work done by the wire itself. This may also explain the lower cut depth of the dry sample and the inability to enter slide width 0 at higher speeds during successive tests.

Conclusions and future recommendations

Cooling

The presence of liquid is vital to the test's ecological validity, both as a cooling agent and a lubrication. Further testing should replicate the environmental aspects seen in a CRJ's working situation as closely as possible. In this case, this could include (but not limit itself to) submerging the test in correct temperature sea water, complete with flow of water reflecting currents or otherwise moving water.

Soaking

Soaking has little effect on the wear rate of Calorfloat in these PV-conditions. It may be more critical to performance should the PV-conditions rise towards the limit of a polymer CRJ.

Scalability

The scalability of abrasive testing cannot be confirmed or dismissed. Further testing, with more samples and a surer testing device is recommended, especially when it comes to the traverse direction of the wire. A higher PV-condition in the test would probably also prove effective in producing satisfying answers.

Dyneema and Calorfloat

Calorfloat seems better suited for cut-resistant jackets than Dyneema at these PV-conditions.

IMPLEMENTATION

With planning and theory in place for the project, the work of realizing the test rig is what follows. The process presented here represents a linear rundown of several iterations and cycles of ideas being bounced, rejected, approved, redesigned and implemented.

Scope Definition

With the background study finalized, the scope of the project was in need of definition. Calora had no exact definition of their functional requirements, which tangled the process of development time-wise. But through the developing process, discussions and dialogs, the shape and definition of the need grew forth. This was further refined during the process, updating documents, demands and limitations underway, but for the sake of continuity the definition of the goal for the project was as follows:

- A flexible, scalar testing rig that can be custom fitted for test specifications and demands set by different projects and companies with possible interest in cut resistant jackets in offshore environments.
- A test rig which can supply a prediction of what will happen in a full-scale situation.

While these goals include research on what demands other companies set on cut-resistant jackets for mooring lines in other applications, such as wind power at sea, wave power and mobile oil production facilities, any such lists of demands are strictly confidential. Thus, the demands presented in this report are based on the demands set by the project itself in regards to specifics set by Statoil, DNV and Calora Subsea.
Initially, the deliverables for the project were a finished test rig and the the associated test results, but due to limitations inherent to the project time constraints, the faculty resources and physical limitations on scalability later described, this changed to the conceptual proposal of a design for a test rig.

Test specifications

With the aid of the test specifications document supplied by Statoil (see Appendix I), a basic set of demands were made to reflect what the machine in the end would have to do. These will be used in Ideation, in order to provide a framework for idea generation categories, and Concept Evaluation, to see whether or not the a concept fulfills the requirements set for it.
Basic demands on functionality, such as wire speed, forces, angles and specifications of materials are all taken from or derived from this document. These formed the basis of the specification of demands for the future test rig. Basically, Statoil's specification states that a 400m long wire of 28-32 mm diameter has to be pulled perpendicularly over a sample with a tension of 147 kN. The contact force between these two increases linearly from 0 to 46 kN. It also states how and what is to be recorded and how the final result should be tested and verified.
Please see Appendix I for the test specifications and Appendix V for the full list of demands.

Chalmers		**Document type** ***Project***	**Specification of demands** Trawl wire abrasion testing apparatus
Utfärdare: Peter Sörensen			***Skapad:*** 2013-02-06 ***Modified: 2013-04-16***
	Criteria		***Goal value:***
	Function		
		Provide accurate specific testing data	
1.	**Performance**		
	1.1	Be a scale model	By a factor X of full size test
	1.2	Apply abrasion	By 32 mm * X steel wire, same type as trawle
	1.3	Apply abrasion	Reflecting 400 m steel cable, single direction
	1.4	Apply contact force	0 – 45 kN * X
	1.5	Allow reading of data	Contact force
	1.6	Allow reading of data	Wire speed
	1.7	Allow reading of data	Wire angle
	1.8	Allow reading of data	Wire distance traveled
	1.9	Allow reading of data	Wire tension
	1.10	Sample compatibility	Let a sample of 254-284 mm fit in testing spot
	1.11	Allow evaluation of sample	Ocular inspection
	1.12	Consistent results	90% error margin
	1.13	Apply same or higher testing forces	than specified in testing
	1.14	Minimize set-up time	Maximum 1 h from set-up to start of test
	1.15	Supply ecological validity	North sea
	1.16	Allow reading of cooling	Temperature of water
	1.17	Supply wire propulsion	146 kN * X, 4.5 knots (2.3 m/s)
2.	**Longevity**		
	2.1	Longevity	5 years
	2.2	Longevity	10 years

Fig 21. Part of the specification of demands. For full view, please see Appendix V

Preliminary calculations

At this point, much of the calculations shown in other parts of the report were done. These formed the fundamental frame which allowed ideas and concepts to be rejected, evaluated and measured in regards of plausibility. They also laid the basis for data used in simulation boundary conditions, initial values and evaluation of their results. Calculations are shown where necessary to motivate or prove theories or decisions, but are otherwise kept out of this report.

SIMULATIONS AND FEM-ANALYSIS

In order to construct a theoretical model describing what happens during the trawl wire encounter, a lot of data must be collected and defined. The main ingredients are the material data of Calorfloat, which may be expensive and time consuming to produce, so giving a definition of what values are needed is a high priority in order to produce those not available to the project. Another important set of data is the specifics of trawl wire, which has to rely on the theoretical layout of a steel cable in combination with the preset forces and material data of steel. Thirdly, the specifications of the test, as lain out and defined by Statoil.
A first, simplified, thermodynamic calculation of the situation allows for a mapping of more advanced simulation construction, using finite element analysis or other mathematical models. Thermodynamic solutions may also help identify problem areas, unknown data and what material phenomena (such as melting, abrasion or galling) may be observed and thus need more literary research.
With material data defined, a computer-aided simulation in COMSOL will be set up to give a prognosis of test results. Since known real-life testing has been made, these can serve as calibration for the model in order to produce more reliable and accurate results should parameters change in, for example, the material composition. However, since no simulation can yet accurately mirror reality, the simulation will need both critical discussion and evaluation. Should it be found lacking it may be rejected as not able to mirror reality or have additional physics added to it in order to produce more accurate results.

In order to construct a simulation representing the situation, a lot of minute facts must be known. A lot of time and effort was put into finding and defining basic material data, work done by the trawl wire and the cooling effect of the surrounding water. Material data was supplied by Calora Subsea, who through a material science company has had lots of tests made on the material, resulting in reliable data. The work done by the trawl wire was derived from the specifications set for the test by Statoil (Appendix I). Through general thermodynamic formulas, forces and speed were turned into work, which is applied as heat to the sample. Of course, some work is lost to heat water and remove material and that work is represented through temperature-based cooling boundary conditions. Convective cooling represent the effect of cold sea water and the continuous reduction of heat accumulation caused by the wire being cold.

Removal of material

Since COMSOL is in essence a fluid flow mechanics program, the first real problem was to fit its mechanics to that of abrasive removal of material. It also meant combining the physics of fluid flow, heat transfer in solids and fluids and structural mechanics.

This is no easy task, since COMSOL has no functionality for actually removing material from a model in the simulation. The solution to this was to first theoretically determine when the Calorfloat covering the mooring line would be torn away by the wire.

Knowing Calorfloat's elasticity modulus lowers to about a seventh of its normal tensile strength at the glass transition temperature, it was established that material at this temperature would suffer structural failure and be removed by the steel cable.

Secondly, since the actual removal of geometry was not possible, the model would have to do the next best thing; making it insignificant. Density, thermal transfer coefficient, heat capacity, viscosity among other variables were at this temperature gradually changed to make the material shrink, conduct heat and affect the next layer of material as if it was not there.

This showed some success, although there were several instances where the finite element analysis couldn't cope with the changes in geometry. There was also the problem with the abrasion direction being one-dimensional (the direction of the contact force) but the heat spreading two dimensionally. The solution taken to this was to make a cross-section of a cross-section, a slice as wide as the wire itself so that the thermal direction was physically constrained by the geometry of the model. Figure 22 below shows the result of this simulation. Because of the 2D nature of the simulation, everything in the third dimension is considered "per unit length". This means the 2D image can be viewed as a cross section of a one meter long block. The material has sunk away as much as a steel wire would have removed, black line showing the original geometry and the yellow border to white signifying the new edge. The simulation could not run the whole way to the end, though, since the deformation was too large for the COMSOL algorithms to cope with. The simulation crashed repeatedly because of this.

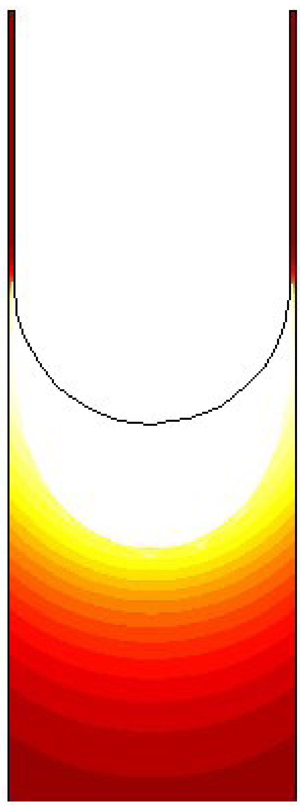

Fig 22. 2D simulation model result. Heat is applied within the crescent and makes the material deform as if removed by abrasion.

To counteract such a limitation, the material was allowed to remain the same shape while the heat transport capacity of the material was increased when removed. This would, instead of actually deforming the material, push a temperature gradient border through the sample that would signify the critical point where material is removed.

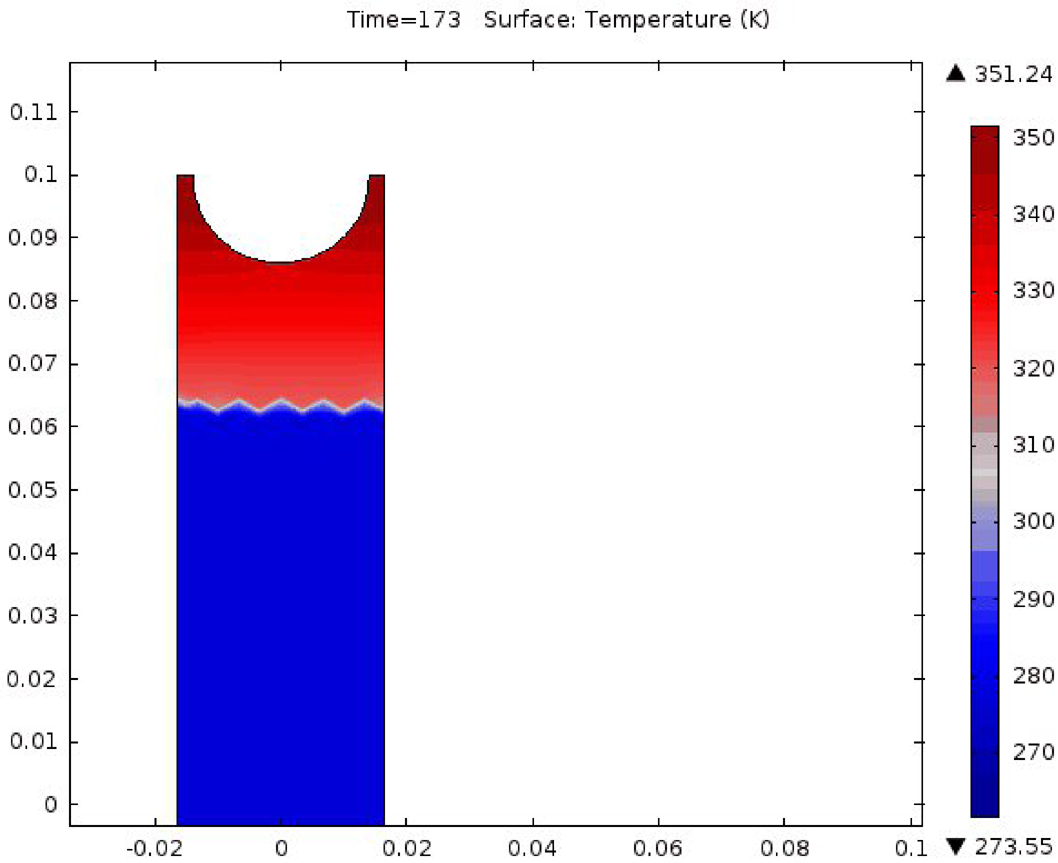

Fig 23. 2D simulation model result. Red signifies abrased material, Blue remaining material and White the current surface

This allows for a more stable simulation of the cross-section, but does not show the distinct cut profile that the deforming simulation had. So while it looks more accurate and stable, it has problems communicating this. Nevertheless, this was the more stable solution and was thus applied to a three dimensional model in order to better describe the event.

Cooling effect of surrounding water

The thermal loss is in essence what keeps the material together under extreme PV-conditions. By leading heat away from the contact area, the temperature is held low and the material integrity sustained. Thus far, this has only been represented through the convection of heat through the material itself, spreading the heat through the sample. The surrounding water will absorb heat from the material and distribute it in its volume, essentially removing heat. If the water is moving, for example through a current, the water will transport heat away from the cut area. What the exact heat transfer rate is between the Calorfloat and the sea water is impossible to determine exactly, but it is possible to approximate. Knowing heat transfer coefficients add inversely, like resistances, the total heat transfer coefficient would be the inverse sum of the inverse heat transfer coefficient of water and Calorfloat. (Frend (2006)) It also means that if the heat transfer coefficients are significantly different, the lower of the coefficients will be the one influencing the total the most.

$$h_{tot} = \frac{1}{\frac{1}{h_w} + \frac{1}{h_C}}$$

But the simple calculations end here. Reasonable values of h range over 6 magnitudes and is not available for every material. It could be 1 or 1 million. (Liedenhard (2001)) But yet another advantage of simulations surface at this point. Since an experiment in full scale has been run by DNV and Calora and the results of these are available, a heat transfer coefficient can be derived from this result. This also with the beneficial correction for any faulty assumptions through other boundaries and inclusion of the abrasive wear of the wire as a heat factor, since the heat transfer coefficient will be based on the result of a real test. Added to this will in this case be the cooling effect of the steel wire, working much in the same way as the water does, since this also affected the real-life test result.

With a parameter set to reduce the friction heat according to Newton's law of cooling, a study was run of several different values for h, starting with the guessed value of 100 W/m^{2}K, stepping towards the convective cooling constant of water flowing at 2 m/s over a 60 mm plate described by Liedenhard (2001); 590 W/m^{2}K.

Although this will yield the cooling efficiency of Calora's land experiment, where the sample was cooled with a fire hose, this will yield a pilot value of the heat transfer coefficient that can be used in comparison and further development.

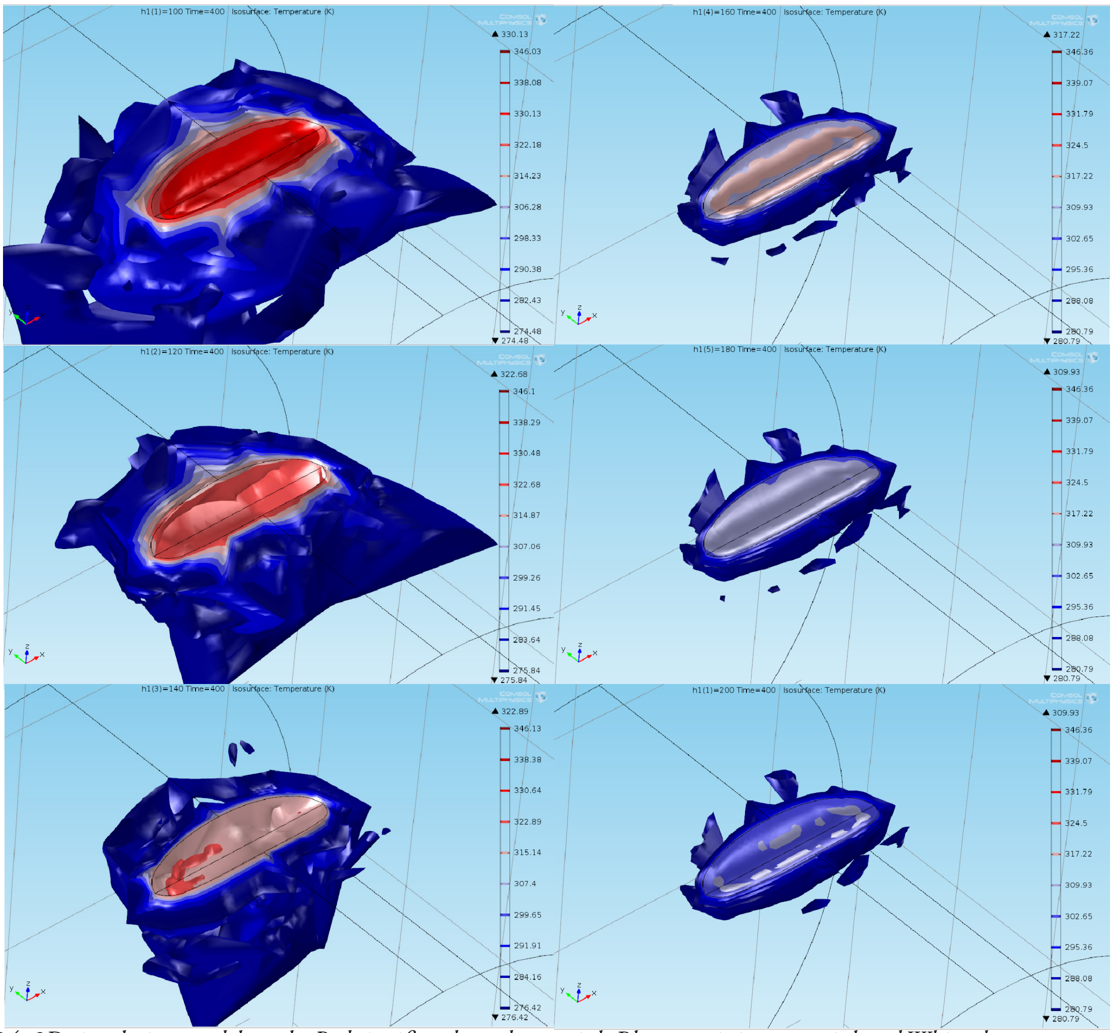

Fig 24. 3D simulation model result. Red signifies abrased material, Blue remaining material and White the current surface. Each image signifies a different value of h. Top left is 100 W/m^{2}K, bottom right 200 W/m^{2}K.

Through visual analysis of the result, it was determined that the sought thermal coefficient was somewhere between 100 and 200, so another parameter study was performed between these two values.

If compared to the result of Calora's earlier testing, the 120 W/m^{2}K cooling produces a volume of Calorfloat heated to abrasion temperature similar to that which was removed in Calora's test.

Result

Thus, a simulation is now constructed that gives an indication of the amount of material removed by a trawling wire. Should the need arise, different conditions can be explored by changing the parameters and boundary conditions of the simulation to match a new specific. Granted, the convective thermal coefficient, h, will vary with temperature, but the simulation may still give an indication of the result of such a change, without even touching a trawler.

IDEATION

In order to find the best solutions, a lot ideas of solutions were generated. Based on the demands presented in the specification of requirements, idea generation was split into several, smaller problems where each idea is to solve a part of the main function. The ideas can then be combined to produce more complex solutions and if they work well together, a concept. The problem and idea categories were "Apply contact force", "Measure contact force", "Measure wire speed", "Fix sample", "Show reliability in results", "Simulate environment", "Provide tension" and "Out of the box ideas". Ideas were then generated through brainstorming and random word association lists and each idea was documented in the form of a small drawing.

Provide tension

There is a myriad of ways to tension a steel cable. Ideas ranged from weights and braking systems to expanding forces to provide tension. Based on simple mechanical calculations, many could be dismissed, since the solution would prove too cumbersome to be useful.

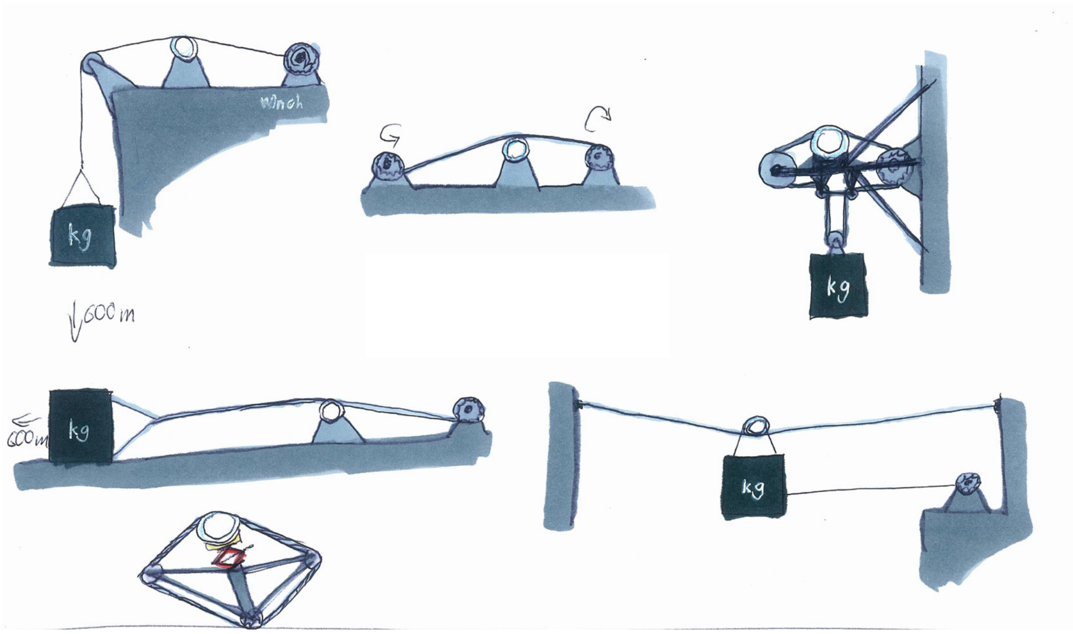

Fig 25. Ideas for providing tension

Apply contact force

There were many ideas of how the contact force was to be generated. Everything from springs to weights and floatation devices was considered. In the end, the jack won, since the forces applied would be too great for weights and floatation.

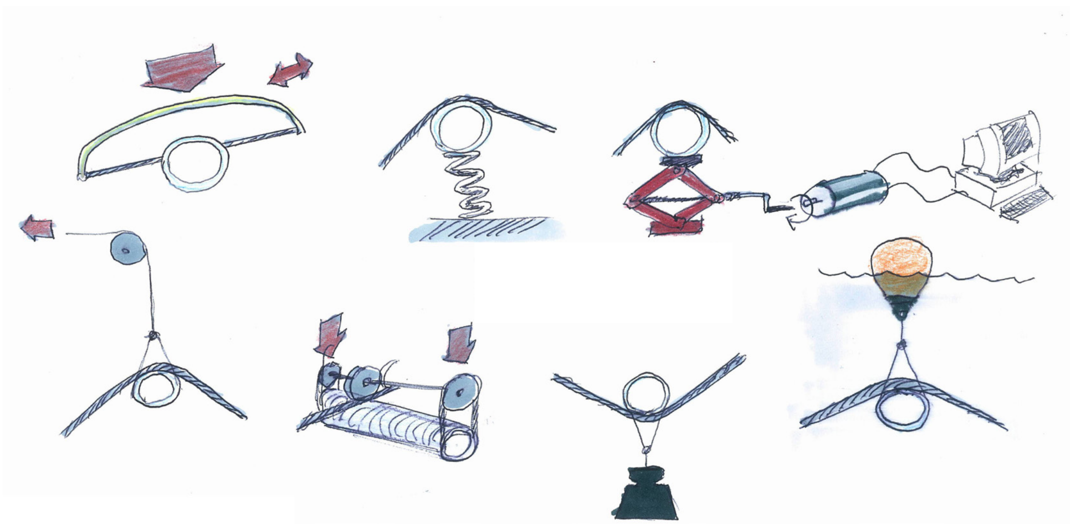

Fig 26. Ideas for providing contact force

Measure contact force

The largest force to measure would be the contact force. The main problem these solutions are to face is the magnitude of the force, several tons, which ruled out almost all ideas.
In the end, the best solution was arose in consultation with the mechanics professor Göran Brännare at Chalmers, who suggested using hydraulics, thus enabling measurement of the contact force through pressure in the piston.

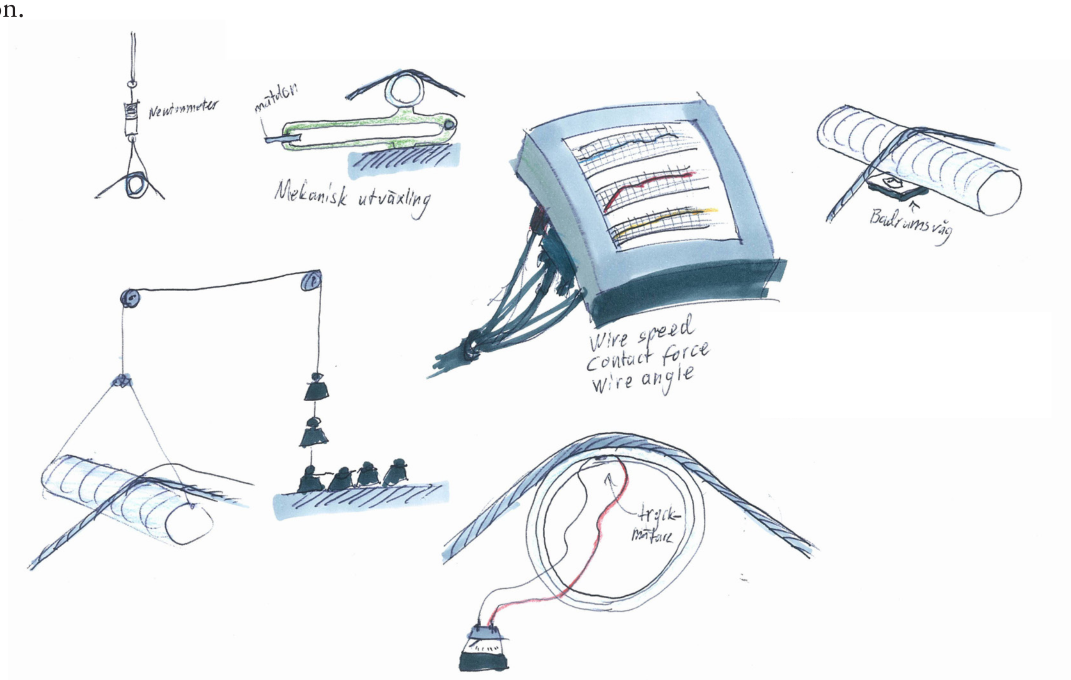

Fig 27. Ideas for measuring contact force

Measure wire speed

Unless wire speed can be read and controlled through the engine of the future test rig, a separate device for measuring wire speed will be required. This will not be presented in any concepts, since it may or may not be required, depending on the final choice of engine.

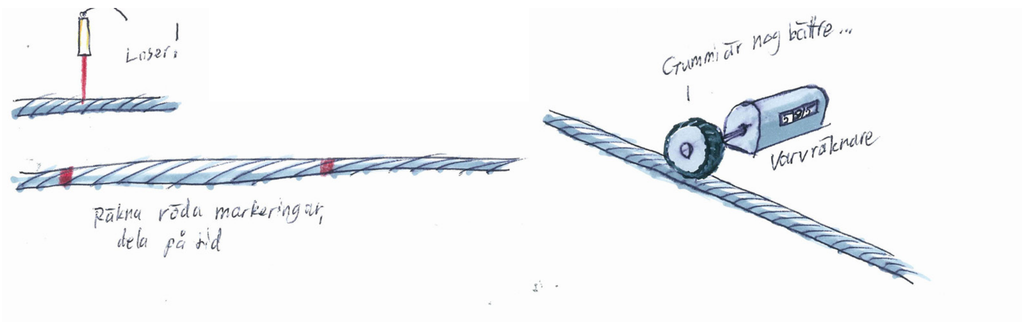

Fig 28. Ideas for measuring wire speeds

Fix sample

Fixing the sample to the rig is a problem no matter how the final concept is made. Since the sample must be available for inspection, as well as interchangeable for new tests, the sample must be removable. It must also be fixed rigidly to withstand the tremendous forces worked on it by the wire.
A simplification that was made based on earlier tests and recommendations from Calora is that the mooring line should be substituted for a steel pipe of the same diameter. This since the mooring line is tensioned with over 200 tonnes and can be regarded as completely rigid. Furthermore, since a machine that could provide such tension in the sample would be tremendously more powerful and expensive than the test rig itself, it is just not feasible.

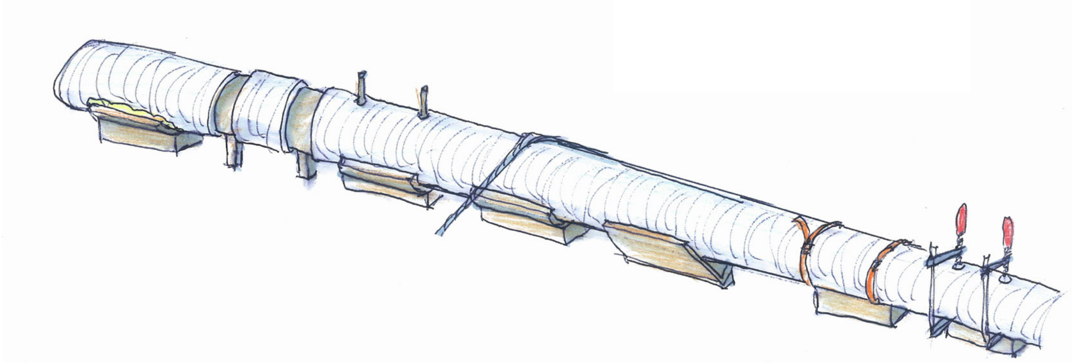

Fig 29. Ideas for fixing a sample

Show reliability in results

Since the ultimate purpose of the test will be convincing potential buyers of the CRJ's capabilities, the test result will have to be very transparent. All previously mentioned measurements will have to be displayed in any documentation of the test results. Peer review or professional evaluation may also help the impression. Other than that, ideas for a transparent rig also surfaced, meaning all elements of the test can be viewed continuously and safely by bystanders.

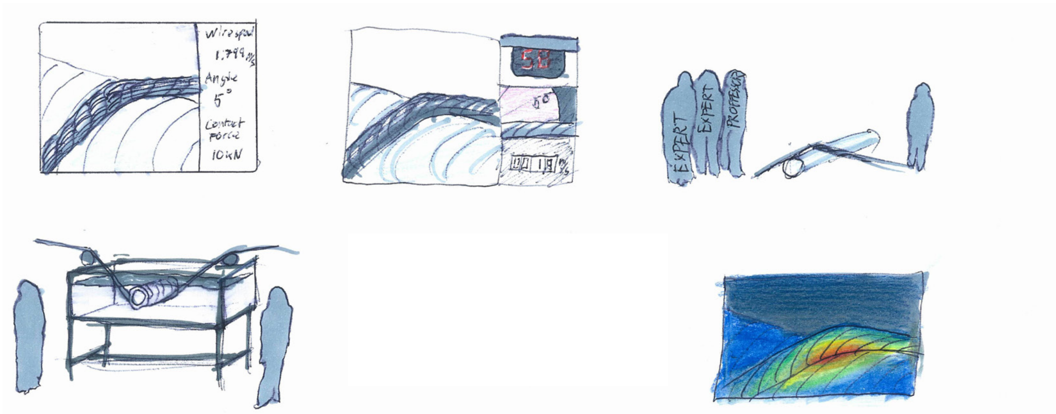

Fig 30. Ideas for showing reliability

Simulate environment

In order to provide ecological validity, the test will have to provide an environment for the test to be run in. Previously, the environment has been simulated through the use of garden hoses and fire pumps, but since this has a very high magnitude of effect on the cooling of the sample, this is a questioned practice. (Hansen (2012)) Instead, ideas circulated around submerging the whole, or parts of the, test. All of which boiled down to submersion of sample, partial submersion and submersion of the whole test.

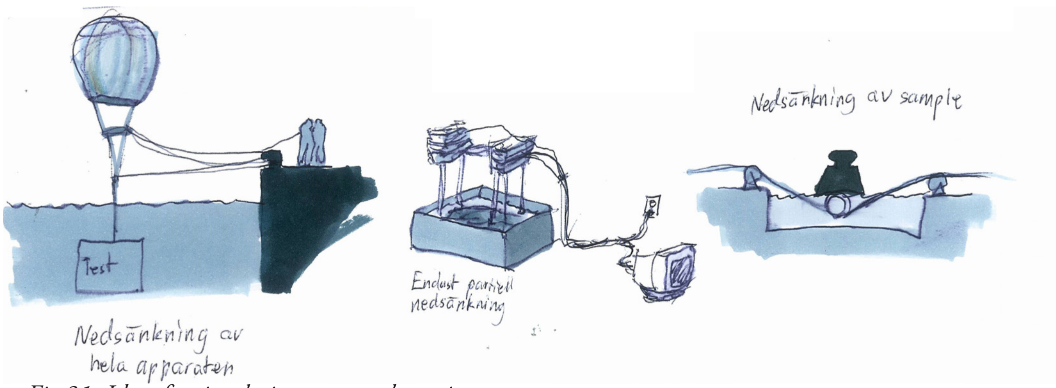

Fig 31. Ideas for simulating water submersion

Out of the box ideas

Under the out-of-the-box idea headline was the ideas which could not be put together through the combination of previous category ideas. Most notable is the original idea of exchanging the round sample and straight wire for a round wire and straight sample, effectively eliminating the need of 400 meters of wire.

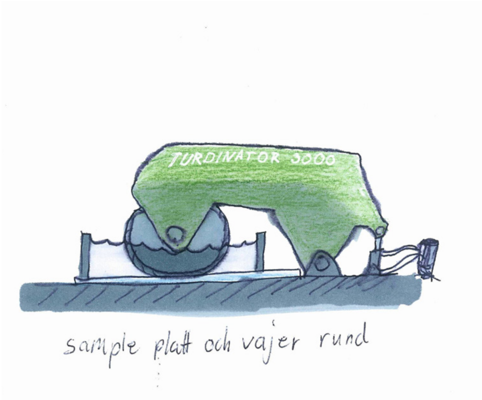

Fig 32. Out of the box ideas

CONCEPTUALIZATION

Ideas were combined in order to produce unique concepts, that would each solve the main problem very differently. Thus, when a large number of concepts were put together, the best solutions and combined ideas can be cherry-picked to form new, better, concepts. Other concepts were eliminated during the evaluation process until four remained. Each solves the problem in its own way and has its own strengths and weaknesses. In order to choose one, the solutions had to be evaluated, pitched against each other, to magnify each strength and eliminate each weakness.
In order to communicate the function and features of the concepts, they were illustrated on paper and made functional models as a basis for discussion.

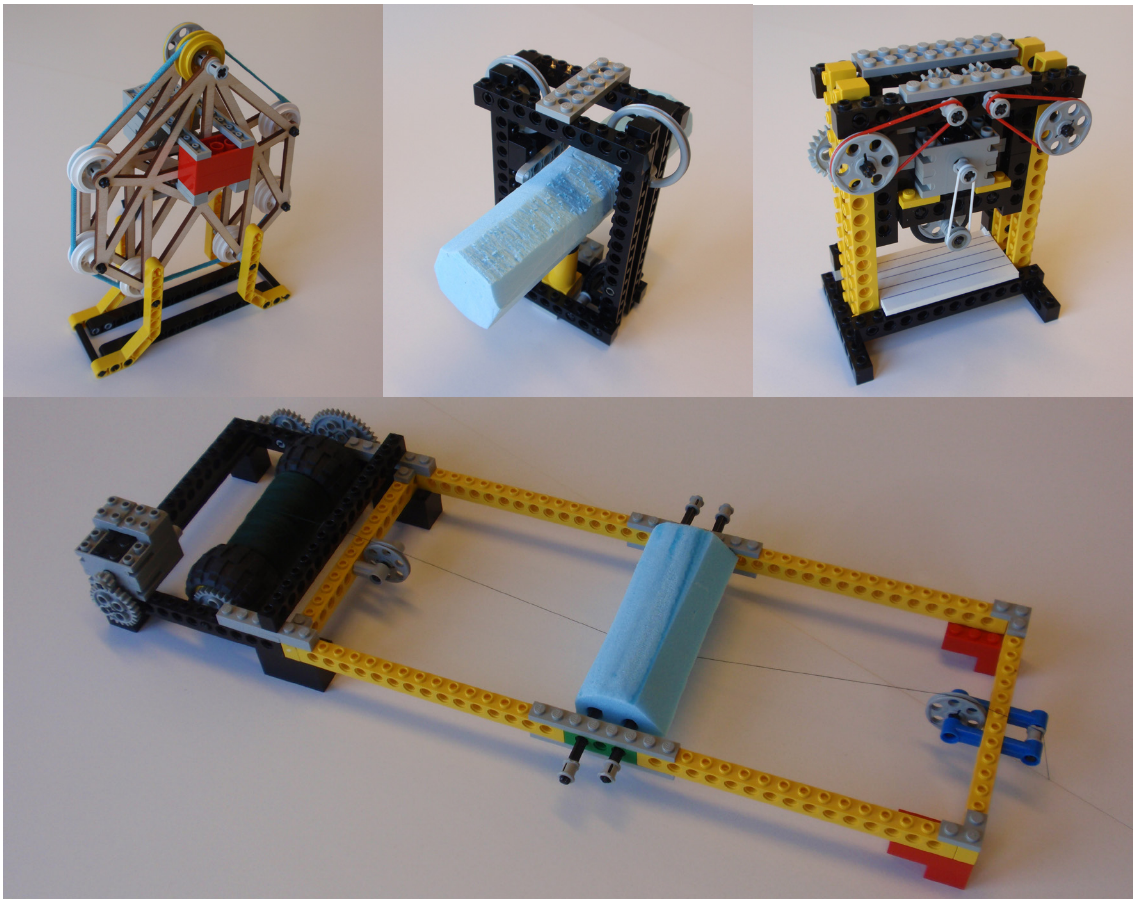

Fig 33. Functional models of four concepts. From top left; Frame, Fix Wire, Rotator wheel and Wire Saw

QUALITATIVE EVALUATION OF CONCEPTS

Frame – The workable looped wire test

The main feature of the Frame concept is a looped wire running on a frame. The sample is then pushed against the cable by a hydraulic jack, keeping all forces aimed outwards, like a star. This will tense the cable and apply the contact force required. The looped cable is driven by an electrical engine at the top of the frame. The whole rig is placed in a salt water bath and the test is run.

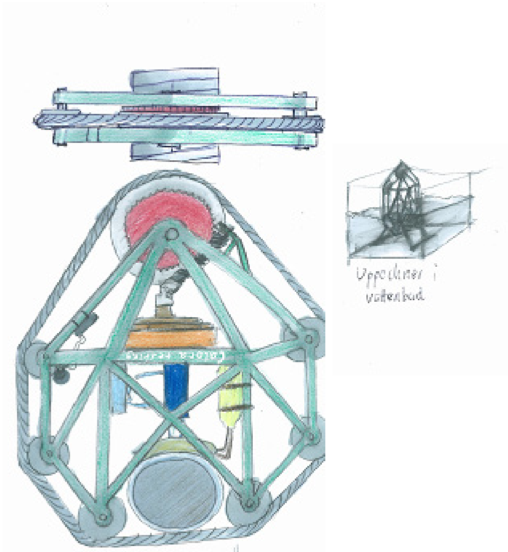

Fig 34. Conceptual sketch of the Frame concept

Strengths

- This is a small experiment, with a small storage volume and little jury-rigging required to set up a test. This means the testing rig can be quickly used, without much planning beforehand, making the tester independent of outside factors like weather and equipment availability amongst others.
- With its comparatively small size, the test rig is flexible. It can be run pretty much anywhere where there is a supply of cooling water to place it in.
- Among the concepts, it is the most potentially good looking. Thus, if manufactured for it, it may be suitable for customer demonstration, fair exhibition or similar events.
- Since there are few improvised and ad hoc parts, the Frame concept is considered to have a medium to short rigging time, depending on how hard it is to find or make a basin for it to stand in.
- Because of its short rigging time and flexibility, this concept is suitable for tests of several samples, perhaps of different material configuration, and verification of the suitability of homogeneous materials.

Weaknesses

- The concept will be suffering from high ball bearings, which will require very tough parts and construction. This in turn leads to an expensive build.
- The concept also requires more specialized parts and new configurations than the other concepts, which results in a longer developing and manufacturing time.

Rotator Wheel – The safe and flexible abrasion tester

The Rotator wheel's main feature is a cable-textured wheel mounted in a hydraulic press. The wheel will turn with the same speed as the trawl wire usually has and the press will generate a contact force. The cable angle is simulated by making the contact force bend the sample into a for the purpose designed slot, thus making the sample bend around the cable wheel the same way the cable bends around the sample. As the 'out of the box' concept, the Rotator wheel suffers from low believability. This is mainly because of the idea that instead of pulling a straight cable over a cylindrical object, let's pull a cylindrical cable over a straight object.

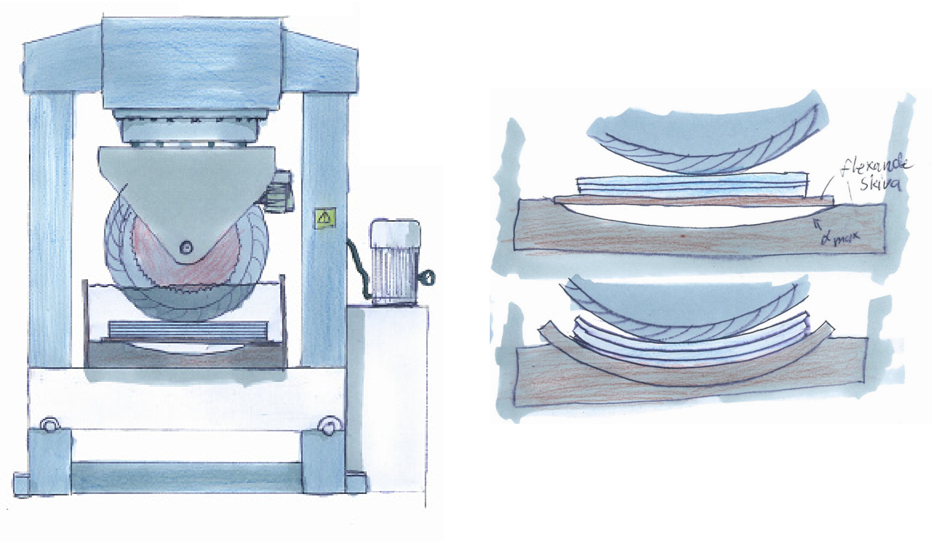

Fig 35. Conceptual sketch of the Rotator wheel concept

Strengths

- This is also a relatively small, space efficient experiment. Storage and operation volume is small enough for it to fit on a normal EUR pallet.
- Due to it's inherent construction it is also very safe for the user. Everything is mounted on a sturdy frame and only a single moving part which is centered far from all edges of the machine.
- The small volume also gives the test rig flexibility, allowing the test to be run pretty much anywhere, given a source of water to fill the cooling bath integrated in the frame.
- While not as reliable for verification, the Rotator wheel is excellent for material testing. Since it simulates a situation similar to a trawl wire incident, comparison between two samples run through the testing rig will give a good indication of which will perform better in the real situation.
- With it's sturdy frame and abilities for high forces, the Rotator wheel may be a suitable concept for an experiment with full forces.
- Since everything is already in place, the Rotator wheel has the shortest rigging time of all the concepts. Simply add water and a sample and run it.

Weaknesses

- The Rotator wheel is the concept least similar to the real situation, meaning it is not very good for verification testing and may suffer from low believability among spectators or critics.
- The cable wheel is a very central part of the concept, and requires to be nearly perfect. This means high manufacturing demands and difficulties in construction.
- There is also the risk of molten plastic from sample sticking to the wheel, altering further abrasion if the sample material sticks.

Wire Saw – The winch and pulley concept

Through the use of pulleys and winches, the wire saw concept illustrates the situation of pulling 400m of cable over a sample. The cable may be wound up on winches, one pulling and one braking, and led through a water bath where the sample is located. By adjusting the height and submersion of the sample, the contact force and wire angle is adjusted.

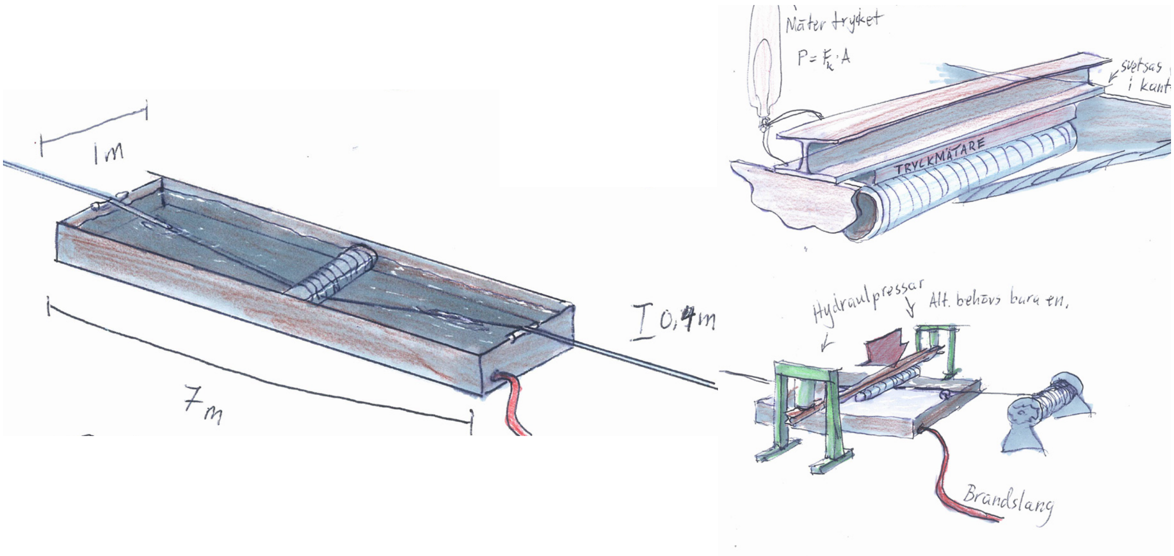

Fig 36. Conceptual sketches of the Wire saw concept

Strengths

- This is the concept most similar to the real event, in that it actually lets 400m steel cable traverse the sample.
- Only standard components are utilized, giving it a simpler manufacturing process.
- Because of its great ecological validity it is suitable for verification testing of finished cut resistant jackets and can be made full scale with strong enough machinery.

Weaknesses

- Because of its configuration, the concept is cumbersome to assemble for testing if it is not always rigged and ready to go. This is a one-off tester, which makes it not very cost efficient to build.
- It requires powerful winching and anchoring since the tension in the cable is high enough to rupture most anchors.
- There is the inherent problem with submerging both the sample and the cable in the vat. Since the cable has to run into the vat without water pouring out, the sample will have to start over the water surface and then be lowered, with the cable, into the vat. This means the sample will not be wholly submerged at all times during the test.
- If the test sample is instead fixed, the angle will not change. This is the alternative to the above and would simulate a constant worst-case scenario instead.
- The experiment is large and cumbersome, since a 7 m basin is required for the wire to run through. This means a heavy, large test that will not be transported easily or has to be assembled before testing, increasing test cost and set-up time. This makes it worse for development testing or continuous testing of several materials.

Cable fix – The moving test

Just as its name implies, the Cable fix concept is based on a fix cable and a moving experiment. A cable is suspended in a basin, harbor or similar and pulled to the correct tension. A small sled with the sample and a hydraulic jack is then pulled along the cable at the speed of a trawler. The jack pushes the sample against the wire according to test specifics for contact force.

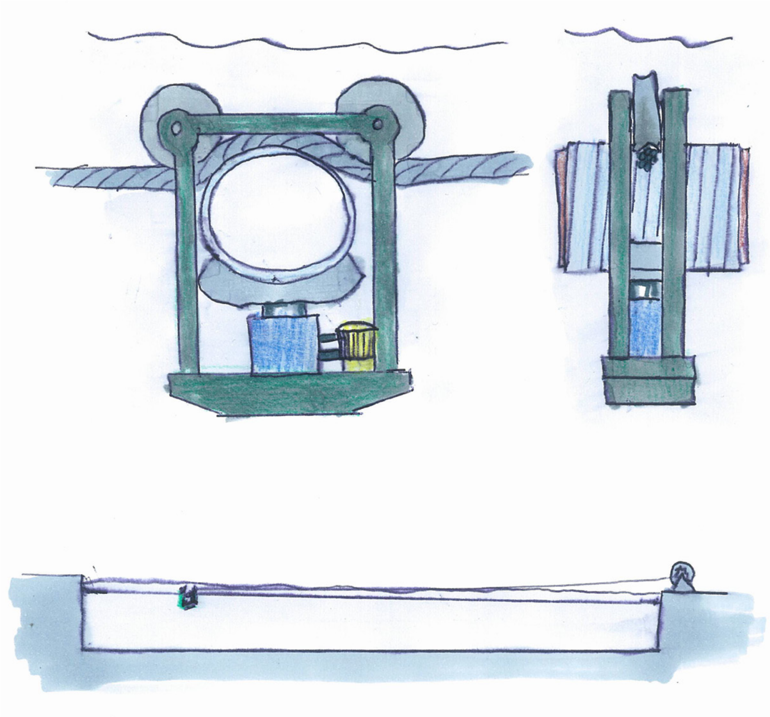

Fig 37. Conceptual sketch of the Cable fix concept

Strengths

- Since tension is in the cable only, the machine equipment required, the winch pulling the sample, does not need to be very powerful. This makes it suitable for full scale testing.
- A light winch and jack are standard components. Cable can be ordinary, albeit long, making this one of the cheaper concepts.
- The test has a good ecological validity, making it suitable for verification testing.
- It is easy to simulate the water currents, since the experiment will be moving through the water.

Weaknesses

- It requires a long basin or other source of water where a cable can be suspended. This may be troublesome to find and locks the testing to specific locations. Alternatively, the test can be run vertically, hanging from a vessel at sea.
- There is no direct visual examination during test, since the whole thing will be moving underwater. This makes it harder to discern what happens at different stages during the test.
- The concept is not suitable for single tests or developing tests due to long rigging time.
- The wagon requires remote control of contact force since it will be moving underwater

Conclusion of qualitative evaluation

Depending on what type of testing is to be performed, a different concept needs to be chosen for further developing. If material development is relevant, the Rotator wheel or Frame concepts should be chosen. If validation testing is the main feature, then the Fix cable or Wire saw concepts should be chosen. If relevant for demonstration, the Frame concept should be chosen.

KESSELRING EVALUATION OF CONCEPTS

In order to get a more tangible assessment of the concepts' worth, the concepts were run through a Kesselring matrix. Basically, this matrix lets the user select a few criteria, grade their importance and then grade how well each concept fulfills the criteria. This is done independently, as not to induce bias towards a favorite concept. The criteria were chosen from and graded according to the specification of demands, prioritizing factors that are believed to be pivotal in a decision situation for Calora. This is the result of the evaluation.

Chalmers		**Kesselringmatris:**									
Utfärdare: Peter Sörensen				Skapad: 130220				Modifierad:		Sid 1	
Kriterier		**Alternativ**									
		Ideal		**Rotator wheel**		**Frame**		**Wire saw**		**Fix wire**	
Namn	w	v	t	v	t	v	t	v	t	v	t
Size	2	3	6	3	6	3	6	2	4	1	2
Cost	2	3	6	2	4	2	4	2	4	3	6
Realizability	3	3	9	2	6	2	6	3	9	2	6
Reliability	3	3	9	2	6	3	9	3	9	3	9
Assembly	2	3	6	3	6	2	4	1	2	1	2
Environmental demands	2	3	6	3	6	3	6	2	4	1	2
Learnability	1	3	3	3	3	2	2	1	1	2	2
Safety	1	3	3	3	3	3	3	2	2	3	3
Believability	3	3	9	1	3	2	6	3	9	2	6
Total		27	**57**	22	**43**	22	**46**	19	**44**	18	**38**
Rel total		1.00	1.00	0.81	0.75	0.81	0.81	0.70	0.77	0.67	0.67
Medel		3.00	6.33	2.44	4.78	2.44	5.11	2.11	4.89	2.00	4.22
Avvikelse		0.00	1.78	0.62	1.36	0.49	1.65	0.59	2.74	0.67	2.25
Median		3.00	6.00	3.00	6.00	2.00	6.00	2.00	4.00	2.00	3.00
Antal svaga punkter		0		1		0		2		3	
Rangordning					3		1		2		4

According to the matrix, the Frame and Wire saw concepts scored the highest and should thus be most interesting for further development. The Rotator wheel is not far behind, though, and should be kept in consideration. The Fix wire concept did not score very high compared to the others.

CONCEPT SELECTION

In the end, after a few weeks of discussion which threw all planning out the window, the Frame and Wire saw concepts proved to be the most promising and were selected for further development. The Rotator wheel, though a creative idea, lacked the conceptual trustworthiness and ecological validity that would be required to convince a potential customer of the validity of the test, according to Allan Hansen at Calora. The Fix Cable concept was also discarded, simply because of the geographical space the test would take up.

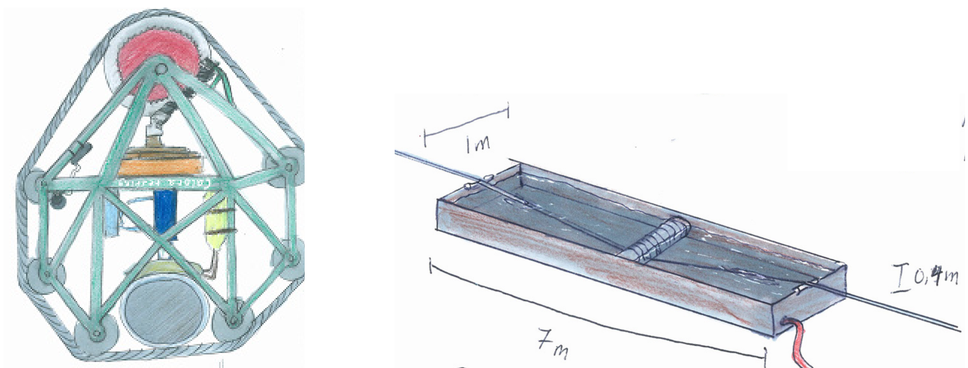

Fig 38. Frame and Wire saw concepts

FURTHER DEVELOPMENT

In order to progress in the design, the two selected concepts were initially combined, giving a single concept several options instead of having two different ones. What would finally be incorporated in the design would be determined by part specifications, cost and availability.

Wire

The main factor deciding which size the rig is going to be is the steel cable. Due to cost efficiency, the rig should be using an as small scale as possible, but since the forces decrease linearly and the strength of the wire decreases squarely, there will be a minimum point where the test strain will break the wire.

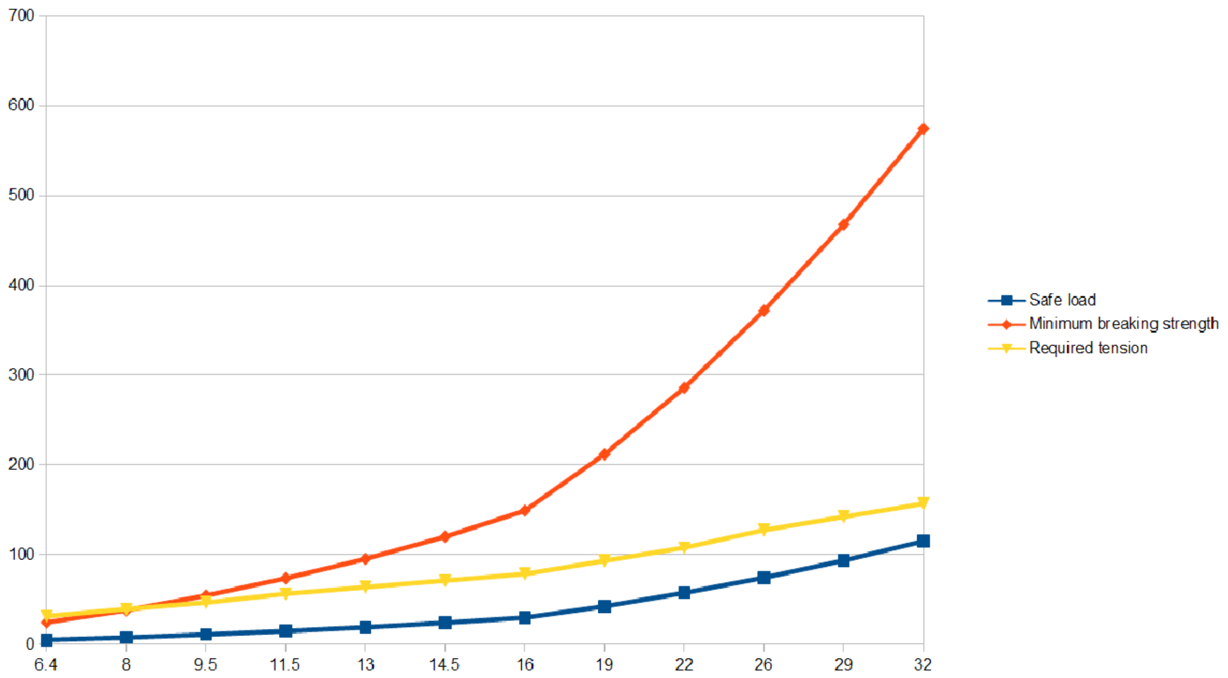

Fig 39. Tension (kN) plotted against steel wire diameter (mm). MBS data: Bridon (2011)

A steel cable breaking is a serious safety risk, especially with forces as high as these. High tensile stress may also damage the wire or cause it to disrupt. Furthermore, the most common wires used by trawlers are not made in all sizes. The smallest size they are manufactured in is 16 mm. (Hurlen (2013)) Choosing this size would secure availability of steel cable and gives the wire a margin of about 2.5 to the minimum breaking strength (MBS) of the wire. (Bridon (2011))
Thus, in agreement with Calora Subsea, the project proceeded with 16 mm wire as the designated scale, giving the test a 2:1 ratio to the full-size test.
The type of wire must, as mentioned, match the structural layout of a trawling wire to ensure correct abrasive wear. There are, however, several different types, each with different characteristics. The most common is the Dyform compact wire, because of its high strength compared to its low cross-section, meaning the wire won't weigh as much, longer trawling equipment can be used and the rolled up wire takes up less space on the winch drum. (Mörenot (2013)). Standard steel wire has been widely used, but not so much now, according to Hurlen (2013). Thus, the wire used should be a Dyform and the 6x26 IWRC was suggested by Mörenot, since this is the most commonly used wire.

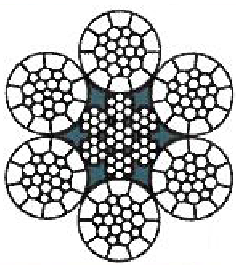

Fig 40. Cross section of Dyform compacted fishing wire (Bridon (2011))

Traction

In cooperation with Laubjerg Vinch AB, the decision of what kind of winches to use was taken. Since 400 meters of steel cable has to be accommodated on the winch drums, the first suggestion would be a very large, double drum winch with some kind of braking device which would provide the tension in the cable. This would allow a cost reduction, in comparison to the original Wire saw concept, since it only needs a single winch.

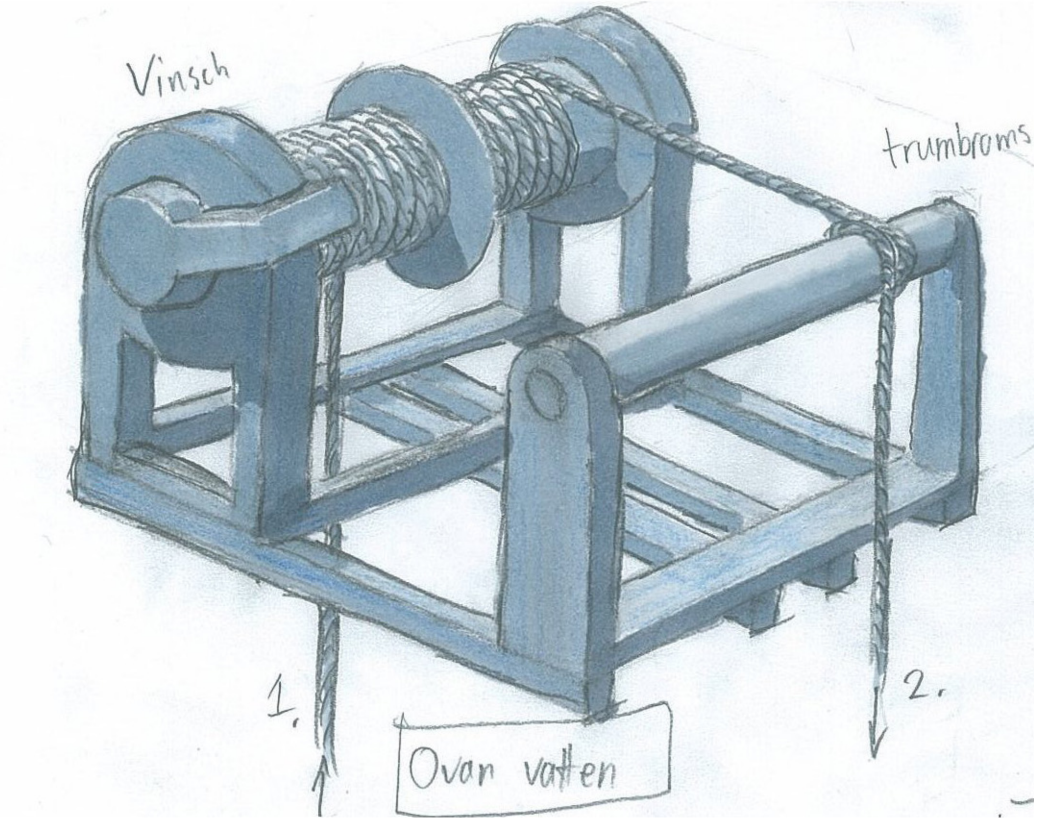

Fig 41. Double drum electric winch and braking drum. About 200 000 SEK for one fitted for 16 mm wire.

However, this would require a large and expensive winch, since it must generate close to half a ton of traction per millimeter of wire diameter in combination with speeds up to 2.5 m/s, and requires a separate traction drum with a braking system. Cumbersome to say the least and carries a few inherent problems.
The most common form of traction device is the single drum capstan used extensively on ships for handling mooring lines and the like. The drawback to handling long lines is the axial movement of the line across the face of the drum. This causes frictional wear and/or rotation of the cable, something that quickly will ruin the wire or cause disruption among its strands. The single drum capstans are best used when low line to drum friction coefficients are encountered and the line can slide axially across the drum face. (Stasny et al (2001))

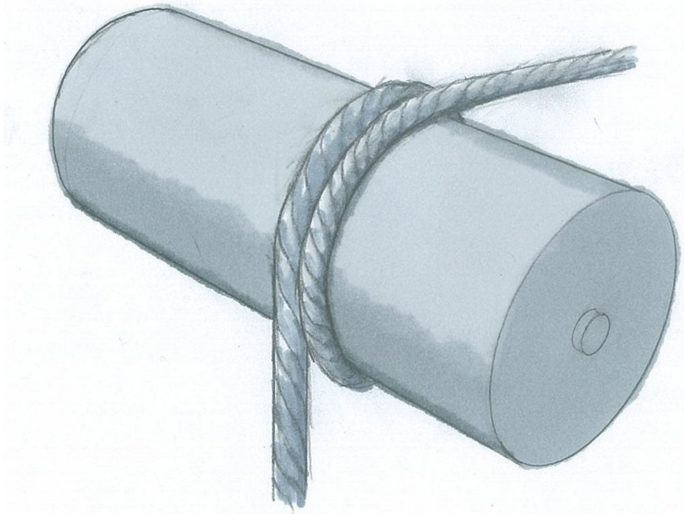

Fig 42. Single drum capstan

Since axial movement in the machine or disruption of a fairly expensive wire is not desirable, a new winch was proposed. A traction winch, which is a device commonly used in offshore and subsea constructions, mooring applications and salvage operations, (ACE Winches (2013) which with a looped wire can remove the constraint of having to wind 400 meters of steel cable on a large drum.

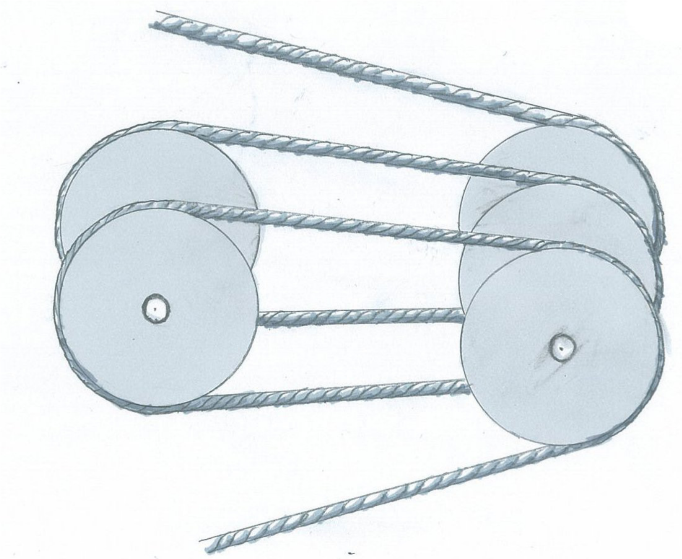

Fig 43. Schematic illustration of a double drum capstan. Each set of wheels represent a drum.

The double drum traction winch with a companion storage winch is commonly used with long lengths of cable. In most cases, both drums are powered and have multiple grooves. The cable is run from drum to drum and groove to groove providing the axial movement without producing the axial friction and meandering inherent in a single drum capstan. (Stasny et al (2001))

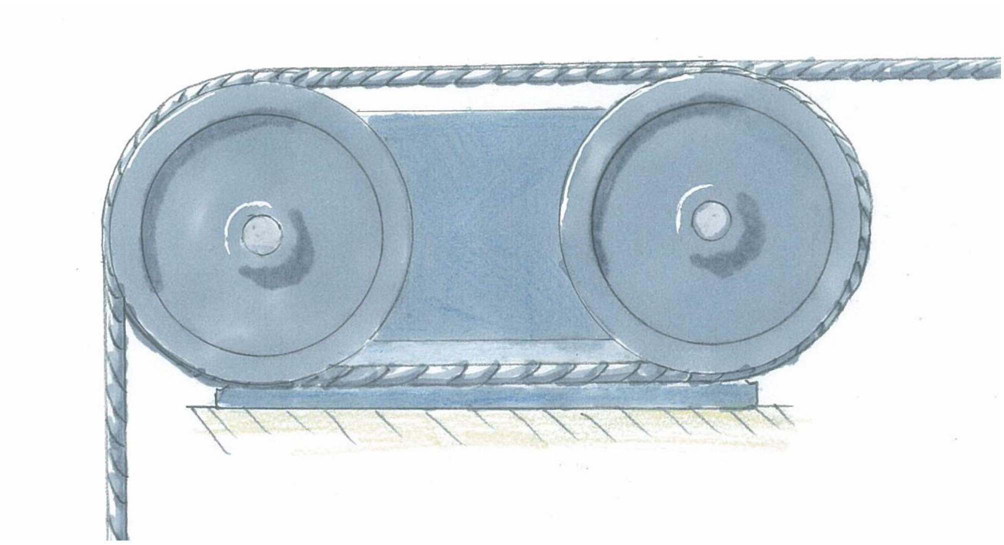

Fig 44. Traction winch

This would provide a stable traction of the looped wire but doesn't solve all problems. The winch does not provide the correct tension, unless braked or if the whole system built to tense the wire.
According to Laubjerg Vinch, such a traction winch, fitted to 16 mm wire, will cost about 140000 SEK and weigh up to 200 kg.

There is, however, issues with splicing a wire of over 500 individual steel strands. In order to make a smooth loop, with no physical protrusions which might affect the test result, the wire has to be made a long splice. This means several meters of strands will have to be wound up, cut at different places and wound together again. This is an expensive and tedious procedure and leaves the risk for individual strands coming loose during testing. (Hurlen (2013)) These issues must be dealt with if the concept is to be reliable. It also means the wire has a minimum length it can be made, which will affect the size of the machine. The longer the wire must be made, the bigger the machine has to be.

Tensing unit

If the looped wire has the correct tension, the engine running the rig will only have to overcome the system friction in order to make the wire go round, meaning a smaller and cheaper engine. Thus it would be desirable to have a separate unit that can set a given pre-tension to the looped steel cable. The braking system described earlier can of course be applied here as well, with some kind of slack take up. This is to this day commonly used in open bicycle gears, where a small spring-loaded arm takes up the slack caused by the gears of different size at the pedals and at the rear wheel.
However, if the frame the steel cable is mounted on was to expand inside the closed loop, the cable would also be tensed, without the use of a braking system, allowing for a smaller winch to run the rig. By mounting a hydraulic jack inside the frame, letting it expand or contract through adjustment of pressure in the jack, the cable can be tensed to the desired tension. If mounted in a square corner, parallel to the wire, the hydraulic pressure of the jack can also be used to measure the tension in the wire, since the force vector and the parallel tension component vector will be the only forces in that direction. A proper support will have to be introduced to compensate for the other tension vector component.

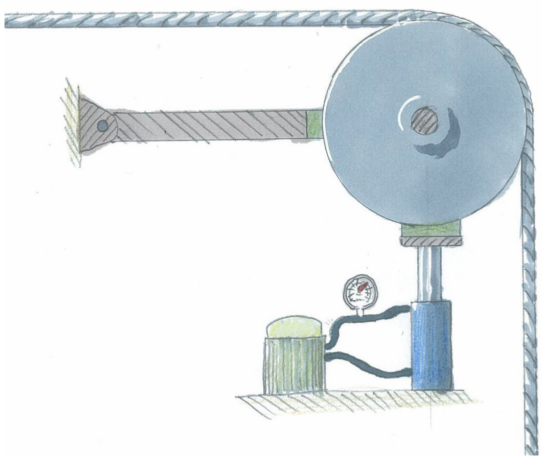

Fig 45. Tensing unit. A hydraulic jack and a sheave.

This kind of tension control will also allow the wire to be relaxed enough for disassembly or exchange of the wire. This will however require the rest of the frame to be open and for the wire not to run through any closed frames.

Contact force unit

Another important and large force is the contact force. According to the testing specifications, the test sample needs to push against the wire with 23 kN by the end of the test. About the weight of an adult black rhinoceros. It starts at 0 kN, however, and increases linearly.

Again, hydraulics seem like the best choice to generate these high forces. Alternatively, a mechanical jack can be used, but since there is a demand on the contact force being measurable, and the hydraulic pressure being just that, a hydraulic jack is the better solution of the two. A sample holder can be welded to the top of the jack, making sure the sample stays in place. To counter the forces of friction, the sample will have to be supported by the frame, opposite to the wire direction. This because the hydraulic jack will be hard pressed to absorb force and momentum in that direction.

Pushing against a wire like this creates an undesirable side effect, though. Just like in a bowstring, the tension of the wire will increase with increased contact force. How much is largely dependent on the span in which the force is applied. In a wire of 8 meters, a span of 2 meters would increase the tension to approximately 170 kN when the maximum contact force is applied. This is dangerously close to the wire's breaking strength at 187 kN and with friction as an additional factor it may well transcend this, risking a cable failure. For a full review of the calculations behind this increase, please see Appendix IV.
To counter this, two support wheels are introduced, reducing the span and taking up the contact force in the frame, instead of letting it tense the cable more.

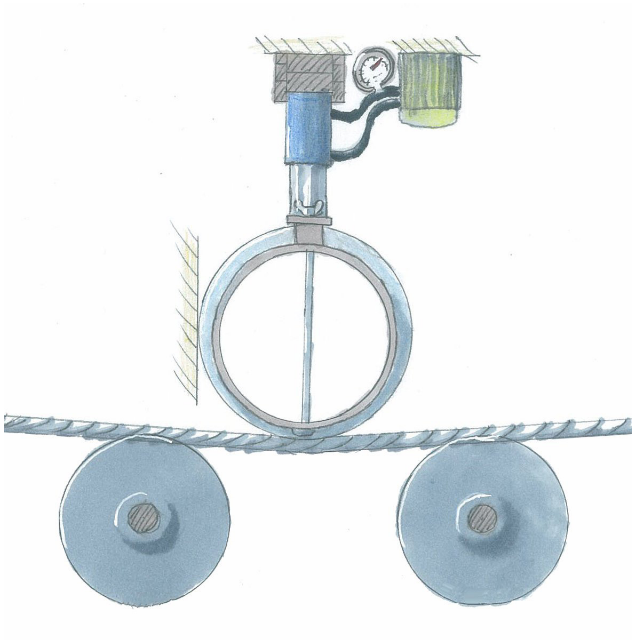

Fig 46. Contact force unit. A hydraulic jack, the CRJ sample and support wheels to reduce the span.

As mentioned in Ideation, the sample will be mounted on a steel pipe, as has been done in earlier full-scale tests by Calora. This is in turn mounted on the hydraulic jack, preferably by a means that is easy to disassemble so that the sample can be removed or exchanged. Furthermore, the sample is going to need some sort of support in the wire traversing direction, since the friction and contact force will generate a horizontal force that would be large enough to break the hydraulic jack or the sample otherwise.

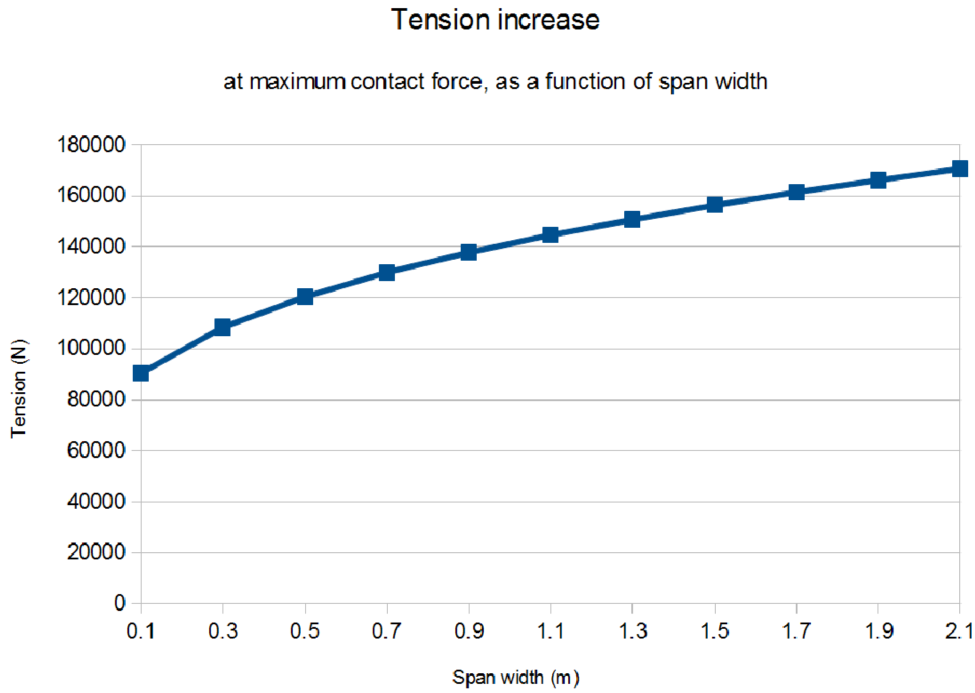

Fig 47. Tension increase as a function of span width

Instrumental Measurements

With both wire tension and contact force already accounted for, the most difficult measurement equipment is in place. Left in the list of demands is wire distance traveled, wire speed and wire angle. While wire angle is not one of the more important ones, speed and distance traveled are both important and closely linked. As speed is the derivative of distance traveled by time, if you know time and one of them, you know both. Thus it is enough to measure time and either speed or distance traveled.

If the traction winch is equipped with a velociometer, or a rotational measuring device, the problem has already solved itself. Otherwise, speed can be measured through either a rpm-counter, relying on laser or actual rpm, or a distance recorder relying on the distance traveled by the wire.

Safety

Since the machine will be working close to MBS of the wire, at very high forces, a breakage of the wire could prove disastrous to bystanders and the machine itself. An 8 meter wire would in a break be subject to an acceleration of close to 8000 m/s^2. As a comparison, during a break event, if the wire was accelerated for a 0.01 second it would reach a speed of 80 m/s. High mass and high recoil creates a very dangerous situation.

R. Verreet suggests a number of safety measures and indication of wire failure in his article "What we can learn from wire rope failures" (2011). He states that the main agents of predictable wire rope failure are corrosion, excessive heat, mechanical and chemical damage. Since no "excessive heat" or destructive chemicals are present, the main factors will be corrosion from submersion in salt water and mechanical wear from entering and exiting sheaves.
The wire is most likely to break in the area most exposed to frequent bending, but as the wire is looped, no part will be more exposed than another. The entire length of the cable will be subject to the same sheaves, bends and forces. Especially the traction winch's back-and-forth construction will have the wire bend and straighten out a lot of times and under high tension. In order to find damage caused by bending and straightening fatigue, the rope needs to be inspected regularly by a professional.
The wire rope can also break internally, if for example a fatigue break if subject to cycles of increased and decreased tension, since the configuration of a steel wire leads to internal strands being stretched more than external in the case of wire elongation due to increased tension. Wire damage from the inside is as likely to cause rope failure, but much harder to detect during an inspection.
Corrosion due to the salt water will have a similar effect. It is, and especially internal corrosion is, a frequent cause for wire rope failure. Internal corrosion will be as hard to discover as internal fatigue failure. The best way to avoid corrosion is of course to keep the wire out of the corrosive element, namely the salt cooling water. This is easily achieved by emptying the cooling bath and drying the wire upon completion of a test run.

Since a wire break has been identified as the biggest threat to personnel attending the machine, the frame is to be extended to form an impact shield that will absorb the momentum of the wire during a failure. It may also serve as a reminder to that the machine is potentially dangerous.

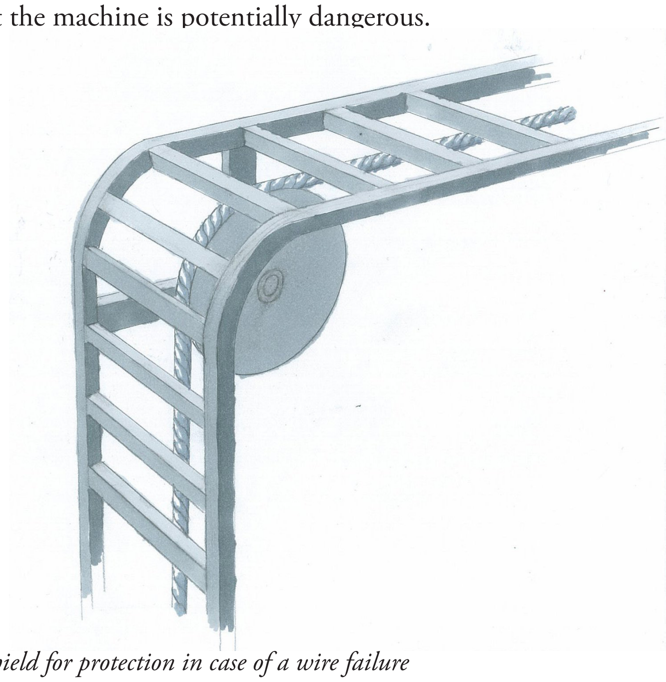

Fig 48. Shield for protection in case of a wire failure

Other safety measures include distance operation of the machine. Since electrical and hydraulic controls are easily moved through the simple lengthening of chords and hoses, there is no reason not to work controls from a safe distance. Granted, the current parts for contact force and wire tension rely on measuring instruments added directly to the hydraulics and would thus need to be read from very near the machine. Since continuous monitoring of these are requirements from Statoil, there will either have to be a translation of the instruments or a recording device attached to each. Doing so will also give a natural means to record data from each instrument and the possibility of a full screen live feed of measurements, something already mentioned in ideation.

Sheaves

The wheels upon which the wire runs are called sheaves and have a critical role in the life length of the wire. Sheaves are designed so transmit loads from the wire rope to shafts or bearings that support the sheaves. The typical load is where the wire change direction 180 degrees, making a U-turn around the sheave, resulting in a sheave load of twice the tension of the wire.

Sheaves must be designed for the diameter of the wire running through them. If the sheave has a too low radius, in relation to the wire radius, the wire will bend too much at each turn and the strands within the wire will move relative to each other. Excessive bending and straightening in such cases lead to fatigue wear on the wire and is a common cause for wire rope failure in cranes. Typical sheave radius is 21 times the wire radius. (Al-Smadi, Protin(2006)) (Verreet (2011)) Thus, the test rig with its 16mm wire would need a sheave diameter of at least 336 mm.

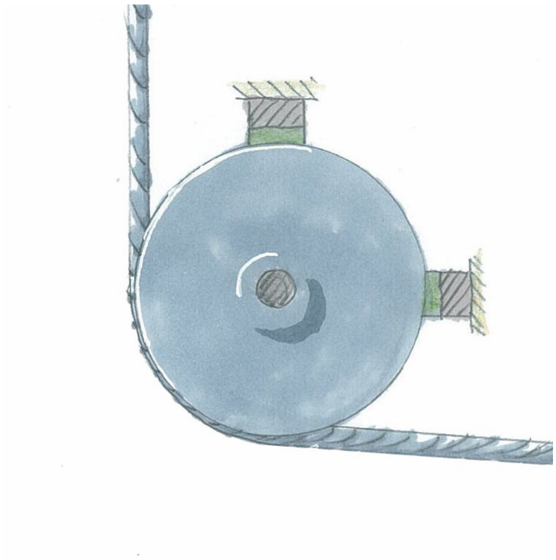

Fig 49. Sheave.

The sheave groove size also have to be fitted for the wire diameter. A too large or too small groove size will damage the wire, since this will cause local pressure increase on the wire running through the sheave. Wrong groove size also increases the risk of the wire jumping out of the sheave due to rotation, vibration or other external force. (Verreet (2011))

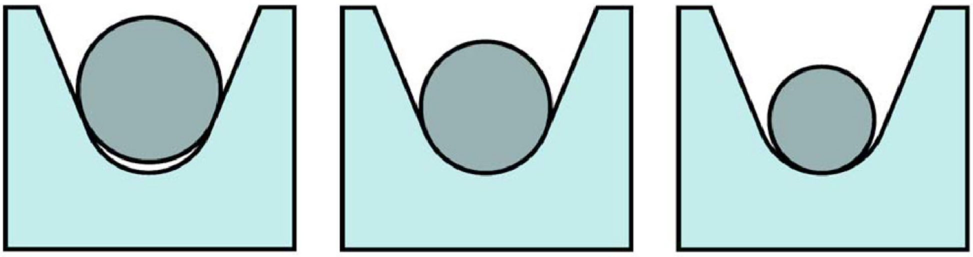

Fig 50. Sheave groove sizes, from left to right: Too small, fitted, too large

The sheaves are also going to need ball bearings and an axis that can take up the load of the tension in the wire. Since each sheave can be fitted on both sides, the bearings can share the load, but since the steel cable goes around the sheave, the load will increase up to double the maximum tension. The net effect is that a sheave bearing will have to withstand the maximum force generated in the wire.

Frame

The main dimensioning factors for the frame is the shape of the machine and the magnitude of forces applied to it. Assuming a frame will be made out of steel girders, welded or bolted together, the construction will have to withstand the same forces of compression as the steel cable endures in tension, plus its own weight and that of engine and other components.

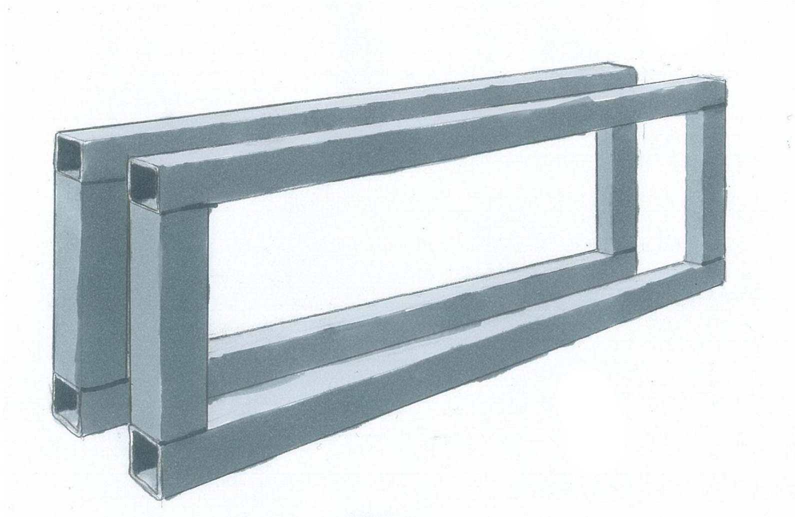

Fig 51. Square frame of hollow square profile extruded steel

Considering a square frame of 2 times 1 meters, one such square on each side of the wire, and assuming a hollow square profile is used, the following applies.

With a safety factor of 5, the framework must be able to withstand 0.6 MN without buckling. Using the Euler buckling formulas it is easily shown that a 50 x 50 mm girder with 5 mm thickness will be perfectly suited for the task.

Euler buckling mode No 4 (Lundh (2001))

$$P_b = 4\pi^2 \frac{EI}{L^2}$$

$$E_{steel} = 200\,GPa$$

$$I = \frac{bh^3 - (b-t)(h-t)^3}{12}$$

Comparing this to the earlier graph of increased tension, this would yield a safety margin of 5 for a span no larger than 300 mm. This would also give the frame an approximate weight of 125 kg and set it in a region of about 3000 SEK for material, welding and paint, using the standard cost of 25 SEK/kg material. (Hansen (2013))

Environmental validity

As mentioned during concept evaluation, the sample is supposed to be submerged in salt water. In order to accomplish this, the machine will have to be designed so the sample can be submerged and sufficiently cooled but all equipment that can take damage from water is at a safe distance from getting wet. As with the original Frame concept, this is solved through a partial submersion in a basin of salt water big enough to fit the machine.

The cooling of the sample will matter most near the cut. And luckily, there is already a mechanical element transporting water to that place; the wire. So as long as there is water surrounding the wire and the wire holds the same temperature as the water, everything should be very close to the true situation. Should additional demands on representing the 0.5 - 2 knot currents of the Norwegian sea (Gyory (2001)) be added, it is a simple thing to add circulation to the vat with a pump, boat motor or similar device.

THE PROPOSED CONCEPT

Here, the result of the background and implementation is presented. Combined, all previous parts make up the finished test rig proposal.

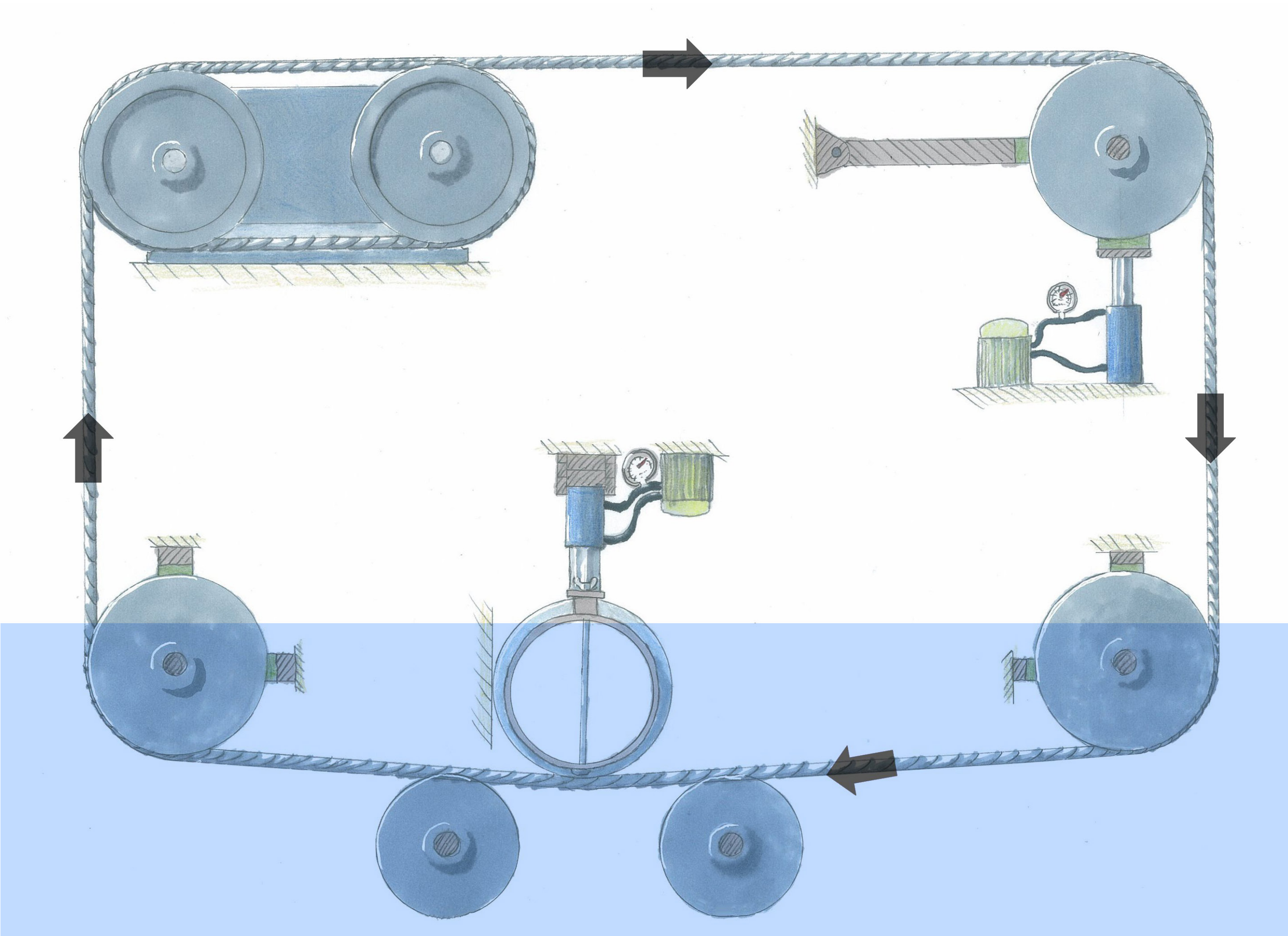

Fig 52. Principal illustration of test rig proposal. Light blue area signifies submerged area.

To communicate its functionality and aid in specifications, a functional model was build of this concept as well. While a long way from a finished blueprint of a machine, this will lay as foundation for future design challenges and discussions.

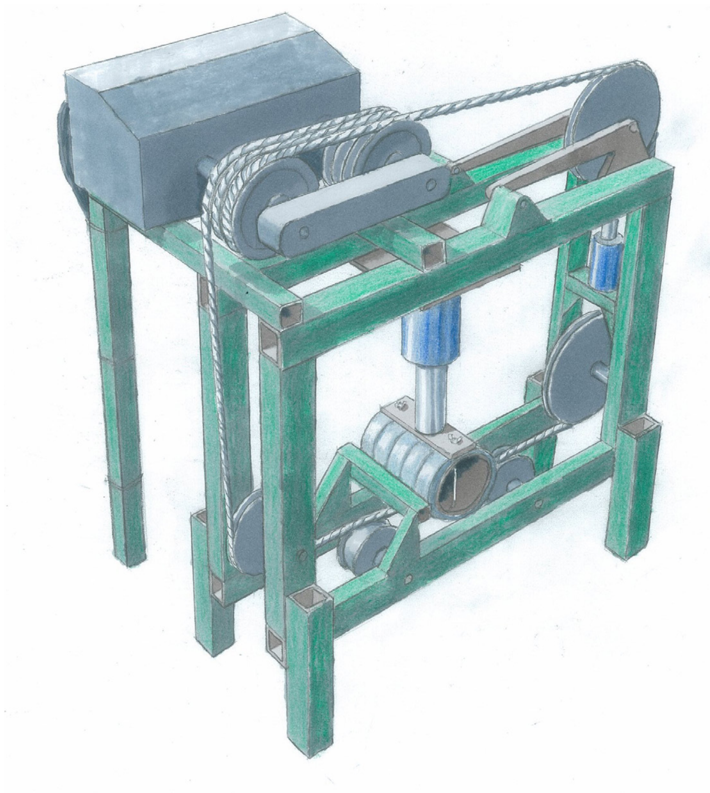

Fig 53. Function illustration of design proposal

Unfortunately, the test rig is in this scale too big and requires too powerful equipment for the machine to be built at Chalmers. There simply isn't equipment, room and manpower to construct it. This is the main factor for resetting the initial goals and deliverables of the project as it makes the project unable to meet the goals without professional assistance.

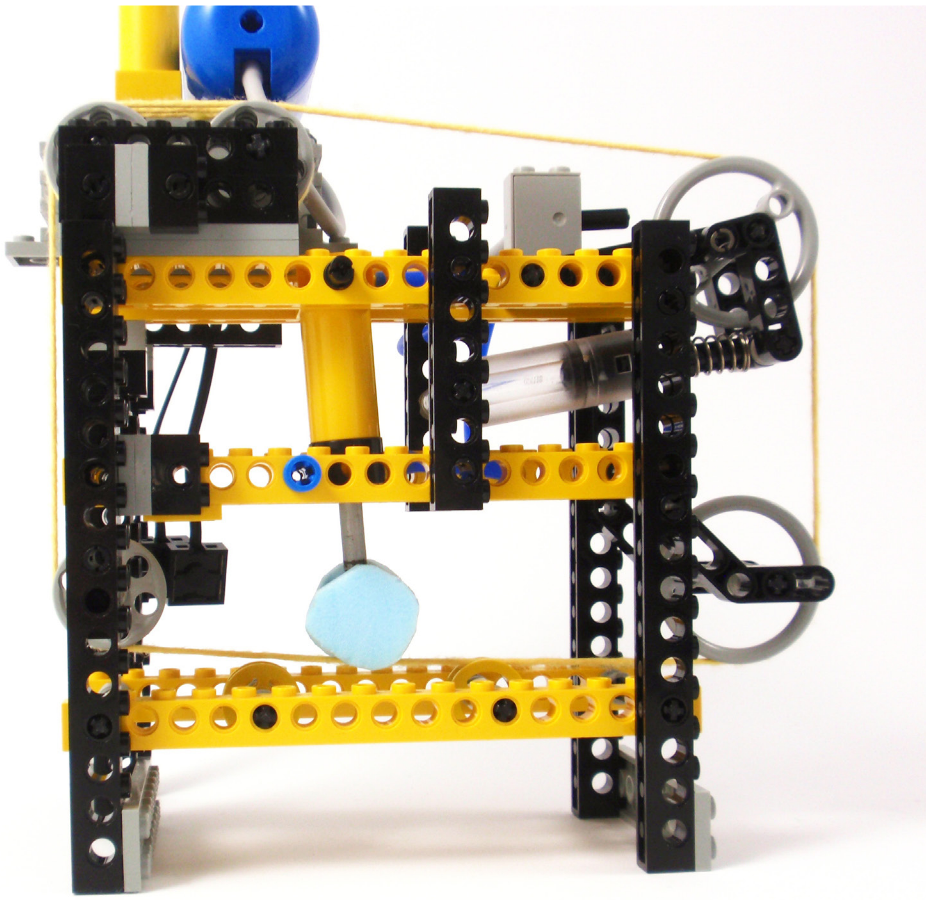

Fig 54. Functional model of design proposal

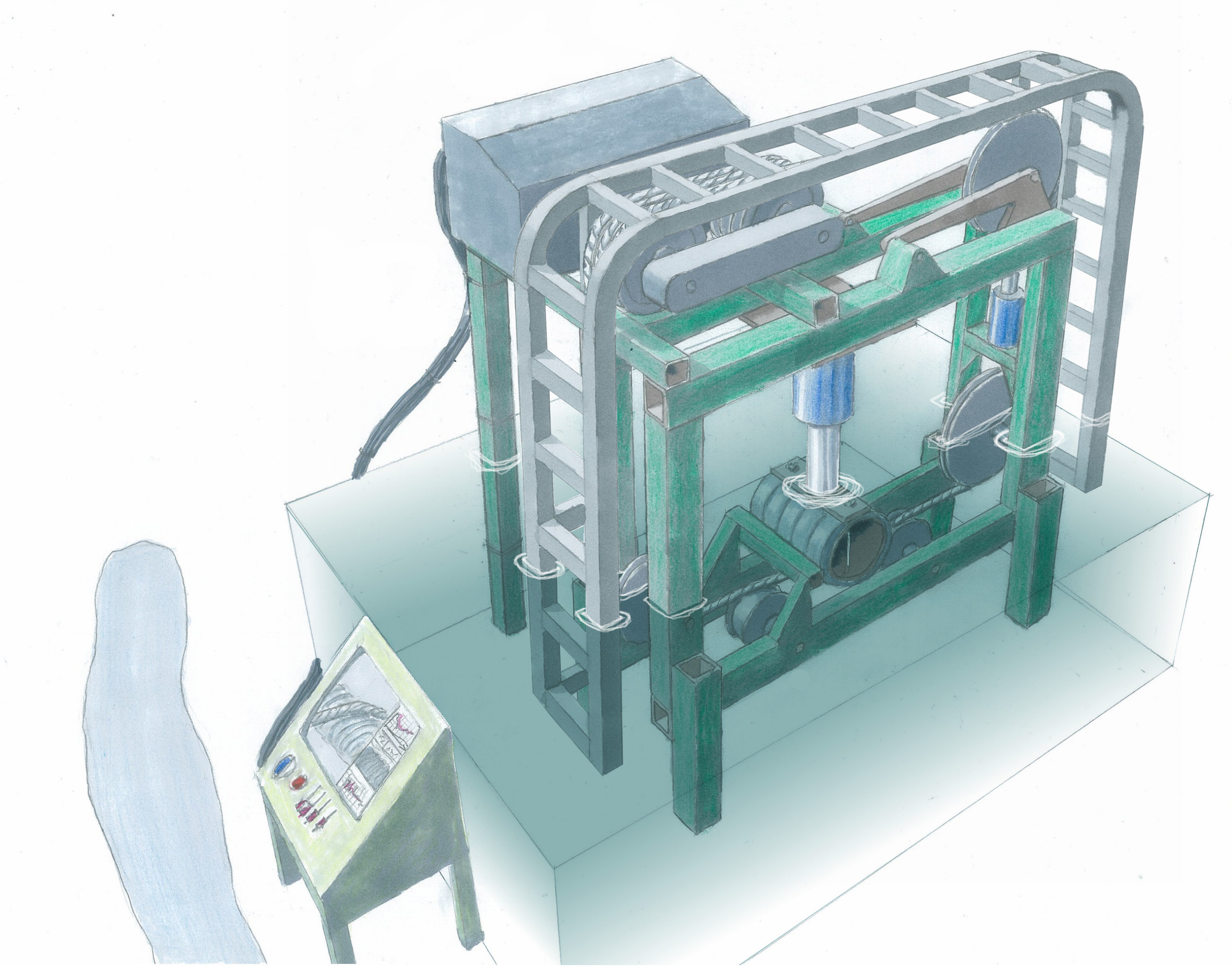

Fig 55. Illustration of all parts of the proposed concept

FULFILLMENT OF DEMANDS

Please refer to Appendix V for the full list of demands.
From what can be determined from the design and construction suggestions, at least an indication of how well the design fits the demands set up earlier can be made. When it comes to performance, all demands except for those associated with testing are fulfilled. Set up time and consistency of results are things that will have to be evaluated on a built test rig, but the design at least supplies the possibility for fulfilling all others. Longevity is another factor that is hard to gauge. Most parts are steel, which inherently has excellent longevity and corrosion resistance. The Achilles heel here would be the looped steel cable, which may or may not suffer damage from test runs and need replacement. On the other hand, the machine is designed to allow for this. If the wire is considered a consumable detail, there is a good chance the longevity demands are met by the rest of the rig. The maintenance demands are also designed for, quite naturally since the demands are fulfilled naturally by steel.

The estimated manufacturing cost, at least for the parts needed, is well below the requested cost by Calora Subsea. However, since the machine has grown during the project, the manufacturing cost, including labor and assistance from constructors, rental and use of a large workshop and any other additional costs may well drive the cost over the original plan. When it comes to the size of the machine, there has to be made changes, since the original demands were set for a smaller scale.
While it may still be moved by truck and forklift, the volume of the test rig will exceed 1 cubic meter. Its weight will also exceed the original specifications. Only the winch will weigh at least 200 kg and the framework is at the minimum another 125. This is a factor for how many operators will be needed during movement of the machine and the equipment required for it. Even though the demand is not fulfilled, there is little to do about it if the scale is to be held. The important border will be when the weight makes the machine immovable.

Aesthetics and design have not yet been evaluated and will remain as a factor for future work. Neither has any patent searches been made to ensure the originality of the design. The physical and cognitive ergonomics of the machine will be largely dependent on the operating equipment which is not determined yet. While designed for safe use and the potential of good cognitive and physical environment, this will have to be a factor for future work as well.

DISCUSSION

Not all things are waterproof. This chapter is about the discussion of weak points in the process, concept and theory presented in the report.

RESULT

The final design ended up much bigger than what everyone had in mind at the start of the project. When I set out, I imagined a test rig that could be used on a large desk, or have its own little table in the corner of an office. But seasons and specifications change, and when I discovered the negative side of the scalability I thought the project would have to be closed, for the initial calculations did not look good. Especially not cheap.

The end result is a huge machine, with considerable forces working in a sturdy frame. That it cannot be built at Chalmers is a pity, but to get correct results it is necessary. While it is half the size of the full-scale test, one can argue that the cost reduction compared to a full scale test may be small now that the design work is done and that the test should be made full scale to ensure ecological validity. However, while true, the reduction in size may be just enough to make the construction of it viable to the company. A bigger machine will be less flexible and may not be movable even by forklift or traverse. And even if the test rig may not yield the same results as a full scale test, it will still give comparable results allowing different solutions, materials and specifics to be comprehensibly compared, so the construction of it is still justified.

Since the project at this stage isn't finished, an evaluation of how well it fits the preset demands is hard to produce. The real question is if what is proposed is what Calora Subsea really needs. On one hand it is a huge machine for a very specific purpose and even in the long run it might be better to improvise a full-scale test to properly convince potential buyers. On the other hand, the Norwegian oil industry is very lucrative and the ability to show just how well your cut resistant jacket withstands a wire may be invaluable in winning contracts that will keep you in business for years. The investment may very well pay for its own cost if only a single potential customer can be won over to Calora's solution.

If the machine was to be reduced even more, to lower costs or space taken, the test will have to be redesigned. This is mainly due to the stresses in the wire and given that the tension is reduced, the design will still work. Or a design like the Rotator wheel could be used instead. However, the pressure induced in the contact area will also be reduced, meaning the total PV value reached during the test will be lower. This may cause the same effect as was observed in Mörenot's testing device, where abrasive force was applied, but not enough pressure or speed to reach the limits of the material. Since the PV tolerance is an important point, as it is over those conditions that the material will stop performing acceptably, it is vital that the test actually reaches this tolerance if the real situation would. But since the PV limit is a factor of two components, there is also the sliding speed to consider. Should the pressure be lowered, technically, the speed can be increased to compensate for this. Unfortunately, in this project there was a set speed to be honored, but in future projects, where this might not be a vital specification, this option should be considered if reduction of size of the machinery is desired.

Another problem described earlier is that of the wire. I cannot say how well a spliced, looped wire would work

under these conditions, nor can I guarantee strands will not start unwinding and ruin the texture of the wire. Sure, it could be considered an effect to simulate the abrasion of an old, worn wire, but since the test is periodic, the damaged part will come back again and again and again. Several damaged parts or protrusions would quickly multiply their effect on the sample by a factor equal to the relation between the looped wire length and the true wire length, potentially ruining the test and requiring the replacement of an expensive, hard-to-manufacture part. The alternative is to take a step back in the process of development and reiterate with a winch able to hold 400 meters of wire and create the tension itself, as described in Further Development.
Since the winch cost doesn't increase very much, according to Laubjerg vinch, this may very well be the path forwards, since it would circumvent the problems with the looped wire. Most of the design can be kept, although the engine will have to be exchanged for a split drum winch and the tension unit for some kind of braking device, probably a double drum system like the traction winch but with brakes instead of engine.

PROCESS

The original plan held about halfway through the project. They say no battle plan survives contact with the enemy and I guess this was a textbook case. I failed to take into consideration the inertia of a company-based decision and it cost me the plan for the rest of the project. But considering how the scope grew with the size of the test rig, the latter part of the planning would have been made moot anyway. And the rest of the planning can be used as basis for further work on the development of this test rig.
Apart from stalling, as can be gleaned from the planning and the above report, the project diverged little from the lain out planning. A few things were cut short, such as design evaluation, but this was mainly due to the design not yet being complete. Alas, 20 weeks is such a short time to develop a product in. Perhaps the project would have benefited from a looser time plan, where each task was allowed to take more time and the result delivered was of lower ambition. It may have helped in creating a more reliable set of theory for things as scalability, but on the other hand the high tempo helped move the project forwards and produce results.

SCALABILITY

The theory of scalability is highly questionable, and lies as a foundation for a huge and expensive machine without having been subject to enough testing, verification or academic scrutiny. I fear this is the weakest point of my design, since I according to calculations may be able to produce the same result as a full scale test would produce but have thus far only a simple thermodynamic example to prove it right. And that is based entirely on theory and models, something commonly known to diverge from reality. Furthermore, it is based on the assumption that material is removed only when warmed up enough to soften. Granted, my experiments at Mörenot show that Calorfloat is indeed resistant to low-temperature abrasion, but it is far from immune to it. The wear rate of steel on plastic has not been considered as a separate factor in neither calculations or simulations, giving them an error margin.

SIMULATION

While simulations are great, they are quite a step behind reality. With that said, I would never have been able to do the millions of differentials my computer can do and the approximation and at least partial prediction is invaluable when making decisions where you'd rather know the outcome of the choices before choosing.
Of course, simulations are as any calculation susceptible to what you give as input. As Kaj Idén at Iden Produktionsutveckling usually puts it "If you give crappy input, you get shit as output." While the material data I've been using is very accurate and researched by professionals, I have had to make a lot of assumptions in order to make it work. I have little reason to doubt the quality of the material data supplied about Calorfloat. What may be a factor here is the sliding coefficient of friction against steel, since this is the major deciding factor in how much work the trawl wire will do. Sure, the situation is still Calorfloat on steel, but under water it is a lubricated condition, meaning a different friction coefficient. Furthermore, the sliding test is probably not performed on steel wire, but on a leaning steel surface, meaning the texture of the wire has not been taken into consideration.
The geometry of the simulation is also open for discussion. In order to get a correct boundary condition, I had to make an indent in the sample, as if the wire had already cut a few centimeters into it. This was to create a surface approximating the changing cut area. A more advanced model may have a preset change in contact area programmed for it, but in this project it was not possible to create within the time constraints.
The most questionable, and by some means the most important, boundary condition is the cooling. This has

to be done correctly, since it is a major factor in deciding whether or not the Calorfloat starts melting or not and in the end I ended up having to guess, since the heat transfer coefficient's true value has eluded me so far. It seems to be a coefficient you calculate, not one you use for calculation and since Calorfloat is a generally new, narrow and untested material, there are no tabled values that I could find with its relation to heat transfer in water.
Additionally, since the simulations program could not remove material in the same way as the wire would, I approximated. This approximation is perhaps not the best, but then again, it worked and the alternative would have been no result at all. Of course, if you trust in simulations too much, no result may actually be a better, and less dangerous, alternative than a result that seems accurate but isn't.

DESIGN EVALUATION

Some demands were not fulfilled by the design. Granted, some could not be fulfilled since the design has not been developed far enough for them to be evaluated or even considered. But there are some that should be, such as the demands on impression. The device may fulfill a vital role in evaluating a cut-resistant jacket for a contractor but if the machinery looks like it can't be trusted, then it may have all been in vain. For future work, some evaluation and research into how reliable test devices and machinery are and should be designed to be believable should be performed and the result applied to the design in order to ensure a positive effect on a potential customer.

CONCLUSION

A compact compilation of the previous parts.

The process of innovation is hardly completed. A lot of work still remains in both construction and evaluation of the thinking work behind it. Through an iterative product development process, the general layout of a test rig is completed, with specifications fitted for the simulation of the harsh elements of the Norwegian sea. It will be able to perform a test simulating the event of a trawling wire being pulled over a cut resistant jacked in the sea, scaled to reduce costs and ruggedness of the machine while maintaining the same contact pressure and sliding velocity as a full-scale test according to the industry specifications, research, experiments and tribological studies presented in the report. The testing rig will be able to test several different cut-resistant jacket solutions to provide a set of comparable results, that may or may not also be an accurate display of what would happen in the real event. This uncertainty is mainly due to the inherent problems in scaling a tribological abrasion test. With the aid of thermodynamics and computer aided simulation, predictions of the outcome of a trawler incident has been made and a model for the event of collision has been made that can simulate changes in the environment, material or abrasive forces.

The test rig proposal is a machine with a looped wire which is run by a powerful traction winch. Controlled hydraulics adjust wire tension and contact forces within the scaled amplitudes given by Statoil's specifications. Using pressure in the hydraulics, the necessary forces can be read and recorded in order to fulfill reporting requirements. In order to provide ecological validity, the cooling effect of the Norwegian sea is simulated by placing the sample and part of the machine in a vat of salt water at the correct temperature, thus ensuring a steady transportation of heat away from the contact area. Since the forces in the machine are very high, safety measures have been taken to make sure operators and spectators will be unharmed should the machine break down violently or during a wire failure. However, the concept is not without its weak points and whether or not it will be realized relies much on the manufacturing of a looped steel cable that will not ruin the testing result. If it can't be reliably manufactured, the design process will have to reiterate from the last step without a looped wire.

The test rig is scaled to half the size and forces proposed by Statoil's specifics in order to reduce costs and ruggedness and based on tribological theory, expert interviews and to some extent own experiments the machine will cut to a depth similar to what a full-scale test rig would, provided a homogeneous sample.

The theoretical model is based on commonly practiced mathematics and finite element analysis. Through the use of material data and forces from specifications, boundary conditions and initial values were constructed to reflect the real situation. Some condition had to be approximated, using test results from a full-scale test in order to calibrate the condition. Though it will never show a mirror image of reality it is complex enough to be able to quickly give a prediction of the effect of changes made to the current set-up or an indication of how or thick a protection needs to be in order to protect a mooring line from trawl wires. All this without even getting close to a trawling wire, mooring line or the Norwegian sea.

FUTURE WORK

No design or product is ever perfect. Here follows recommendations for future work and how to continue the work started by this thesis.

This project will be continued outside of the master thesis since there is still a lot of work to do on the design, construction and testing of the rig. The first challenge to meet will be the looped wire, since this is the biggest construction uncertainty. Depending on how well this goes, the rig will either be constructed similarly to its current design, with modifications depending on how construction evaluation, or will have to take a step backwards in the process, reiterating the development and continuing on the path where a single winch will generate tension through the pulling of a 400 meter steel cable.

When a final design has been acknowledged and accepted by Calora Subsea, the building will commence. Plans for this are still uncertain, but since a larger workshop is going to be required, the building of the rig will probably be located in Norway, close to where it will be used.

Specifications of controlling, evaluation of safety, testing specification and documentation are all events in the future that will have to be addressed in the coming future development.

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APPENDIX I – EXCERPT OF TEST SPECIFICATIONS

Mooring line particulars:

- Minimum Breaking Strength (MBS) 2000t
- Tension in polyester mooring line during damage event: 10% MBS
- The test samples need to be soaked for a minimum of 8 hours.
- The test samples are to be cycled for a minimum of 100 cycles between 2 – 50% of the Minimum Breaking Load (MBL).
- The test samples are to be tensioned up to 10% of MBL prior to executing the CRJ testing.
- At completion of the 400m run of wire rope the sample is to be tested for residual strength up to 40% of MBL.
- After a damage event, the mooring line shall have a residual strength of 40% of MBS

Steel wire particulars:

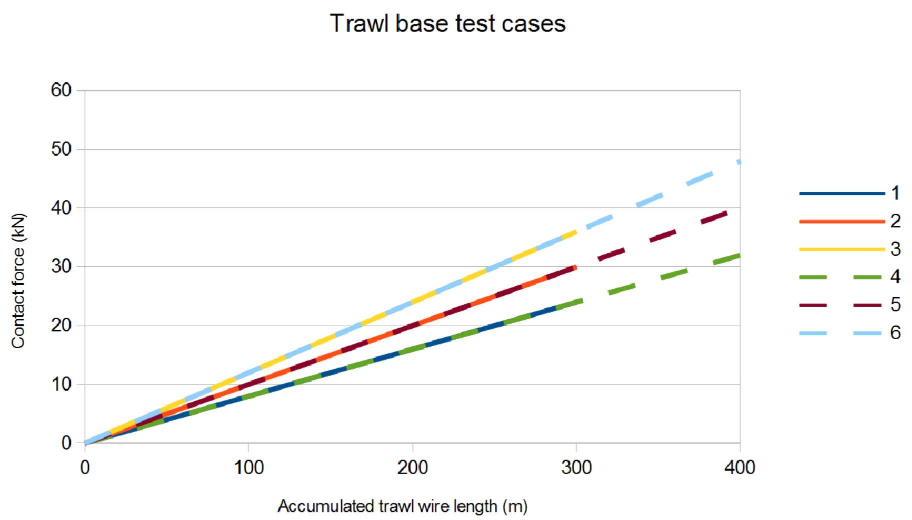
- Diameter D=28-32mm
- Tension during damage event: 147kN (15 tons)
- The state of the steel wire should be realistic with respect to abrasion characteristics. This implies replicating a used (and potentially abraded) trawl wire for testing.

Interaction between steel wire and mooring line:

- Wire angle relative to mooring line (this parameter is changing with time)
- Wire velocity: 2.3 m/s (4.5 knots)
- All wire sliding need to be in the same direction relative to the polyester rope

C. The following are full scale tests required to complete the CRJ test program

1. Base Case – High Velocity 4.5knots, 300m wire rope, at 25kn – record
2. Second Case – high velocity of 4.5knots, Increase the contact force by 20% for 300m wire length. - record
3. Third Case - high velocity of 4.5knots, Increase the contact force by 40% for 300m wire length.
4. Base Case Test Continued – after the 300m then extend the design curve to 400m of trawl wire while maintaining the contact force/wire length ratio. - record
5. Second Case Test Continued - Once complete then continue second case to 400m of trawl wire while maintaining the contact force/wire length ratio. - record
6. Third Case Test Continued - Once complete then continue to 400m of trawl wire while maintaining the contact force/wire length ratio. - record



D. Cut Resistant Jacket Test Setup Guidelines:

The following is a set of guidelines for developing the test procedure for completing the testing requirements in Section C.

1. The contact between steel wire and polyester mooring line is shown in Figure 1. The wire slides across the rope at the high velocity specified in Section C in a single direction. The wire is to remain in the same location on the rope, and at an angle of 90 degrees as seen on the top view relative to the mooring line

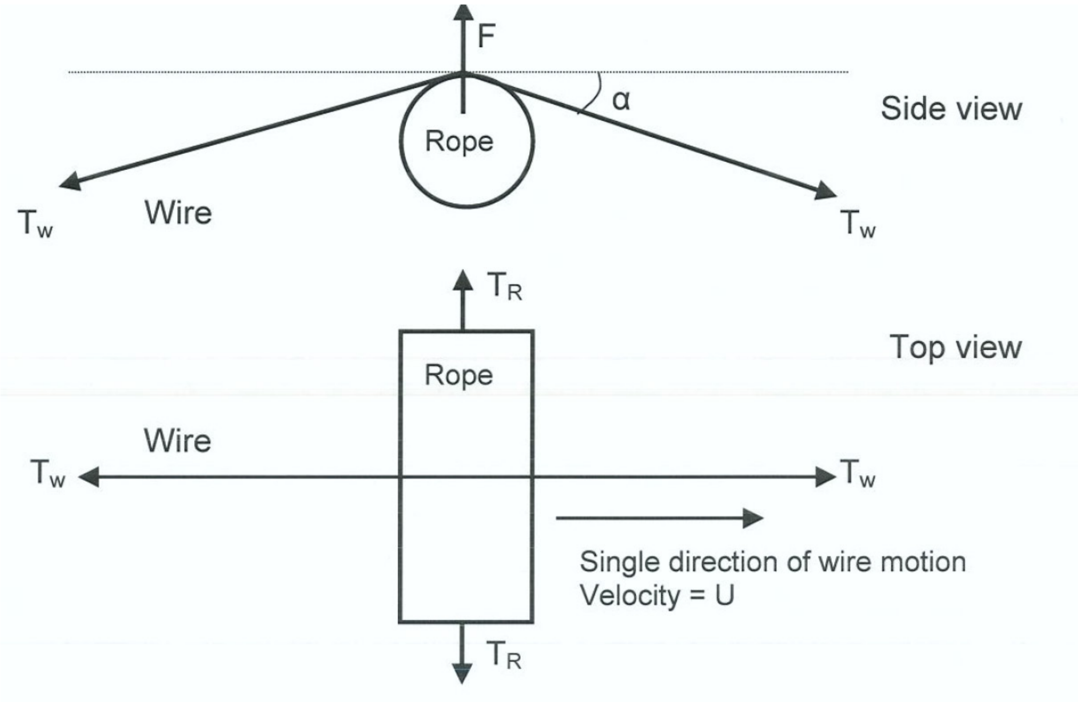


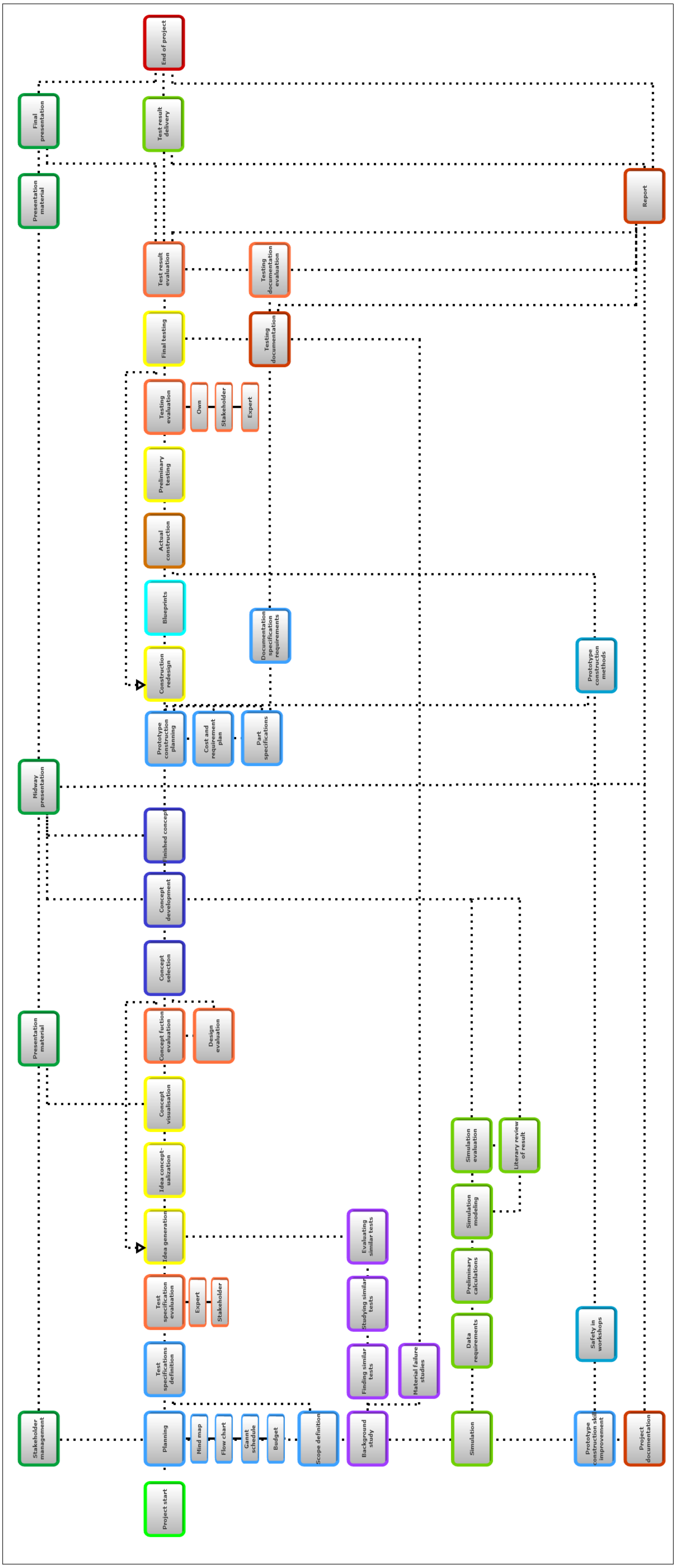
Figure 1. Sketch of contact mode between steel wire and polyester mooring line.

2. The test samples need to be soaked for a minimum of 8 hours.
3. The test sample should have water continuously running at the wire and rope cross section to reduce heat buildup and portray a more real scenario to the actual trawl event.
4. The test samples are to be cycled for a minimum of 100 cycles between 2 – 50% of the MBL.
5. The test samples are to be tensioned up to 10% of MBL prior to executing the CRJ testing. The tension is to remain constant throughout the test as the rope elongates while subropes are cut.
6. At completion of the 400m run of trawl wire rope the sample is to be examined for the number of subropes intact and recorded then tested for residual strength up to 40% of MBL and held for maximum of 10 seconds.

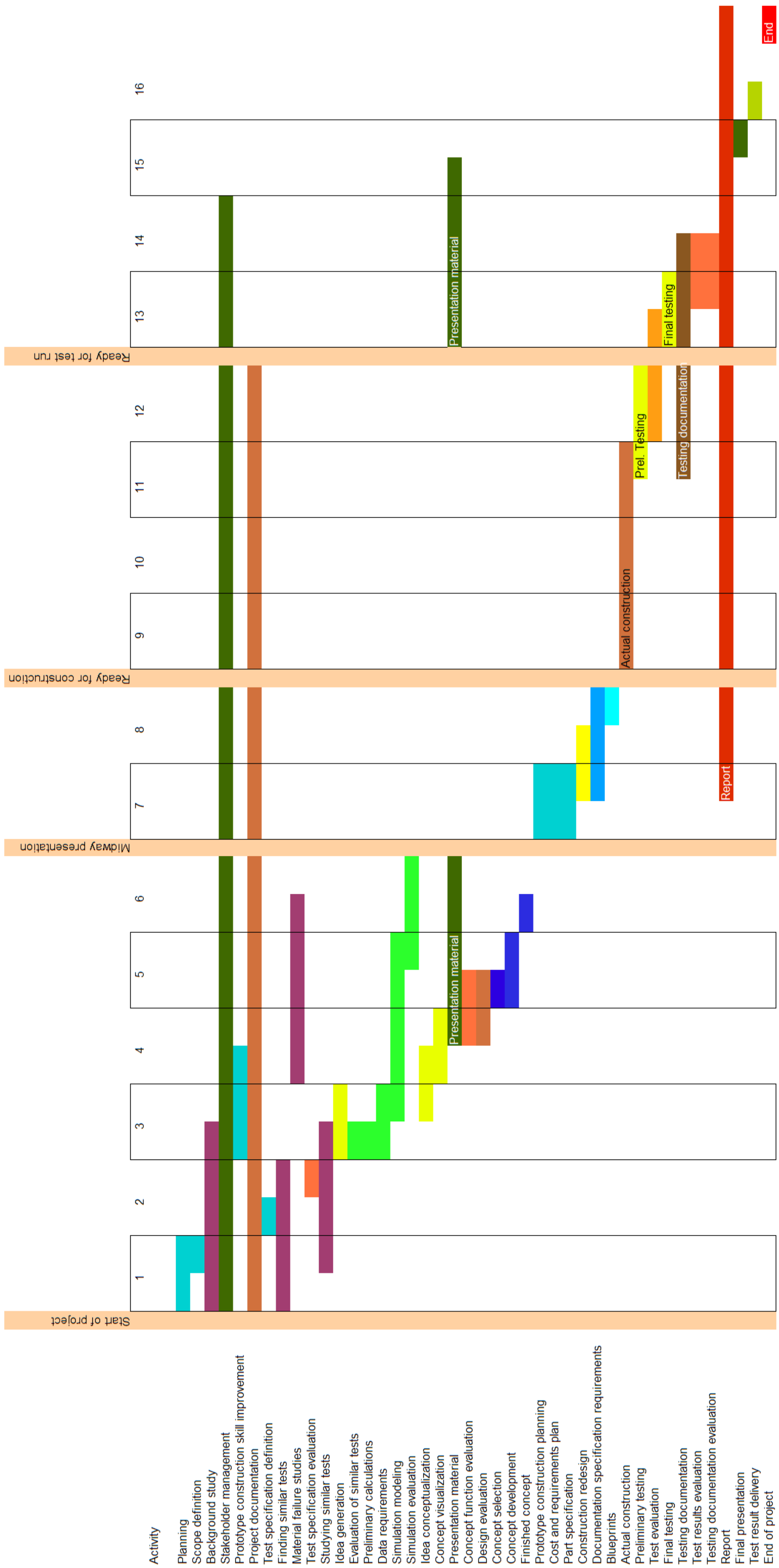
E. Reporting Requirements:

1. Constant monitoring of contact force, tension, velocity and travel distance required for the trawl wire. Constant monitoring of the tension and elongation for the polyester rope is required.
2. Description of the proposed polyester rope (MBL, number of sub-rope, etc) and the cut resistant jacket including application and interaction with the load bearing ropes.
3. Description of the test setup
4. Description of instrumentation, sampling frequency, tolerance.
5. Record the residual strength at every 100m of traveled wire rope length as a data point is requested.
6. At the end of each step in Section C, calculated residual strength based on the number of undamaged subropes is required.
7. Recording during the CRJ testing and reporting is requested to be similar in quality and content as completed previously for the DNV testing conducted in June 2012.
8. Additional graph showing the relationship of the capacity of the polyester rope versus the wire length sliding over the polyester rope for different levels of constant contact force.

APPENDIX II – FLOW CHART

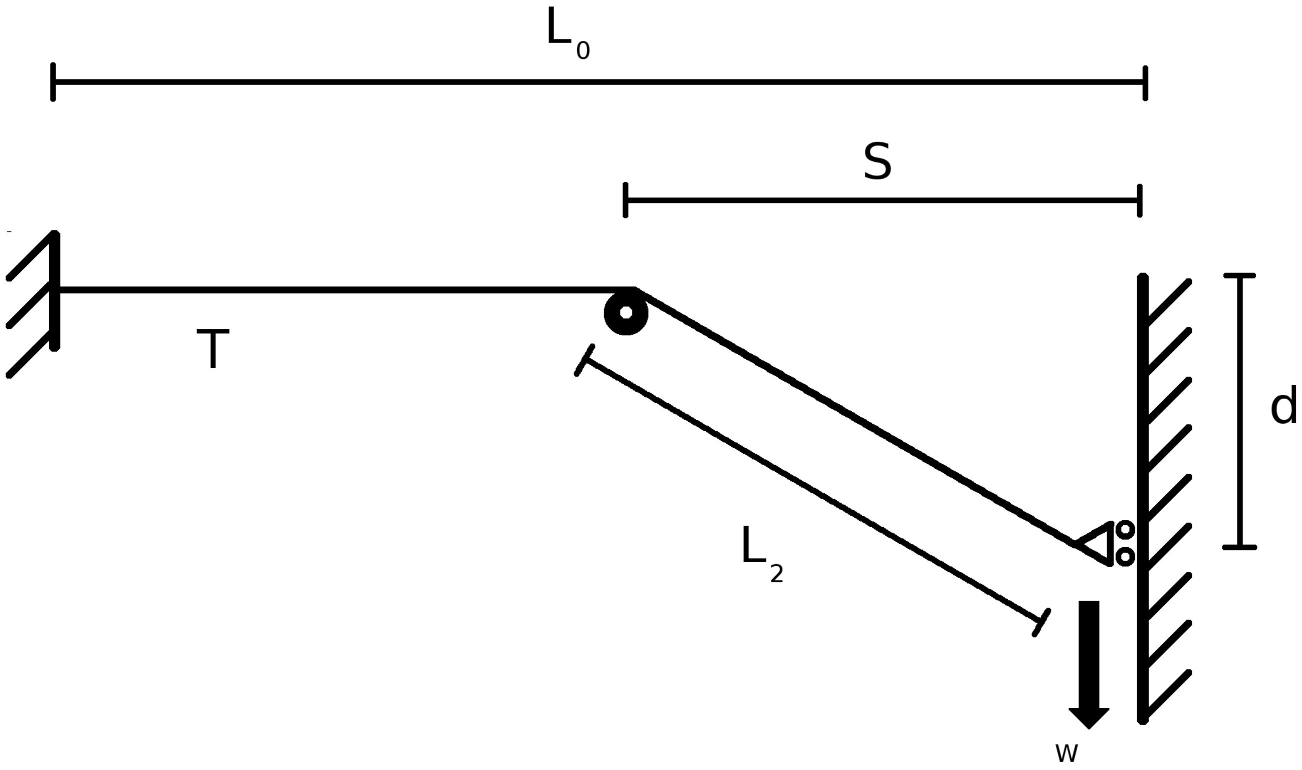


APPENDIX III – GANTT SCHEDULE



APPENDIX IV – CALCULATIONS

Tension Increase



By geometry: The new length of cable in the span is equal to the length of the span plus the elongation due to deformation through increased tension.

$$L_2 = S + \frac{L_0(T - T_0)}{EA} \qquad (1)$$

By Pythagora's theorem: The new length of cable in the span is equal to the square root of the sum of the squared span and distortion of height.

$$L_2 = \sqrt{S^2 + d^2} \qquad (2)$$

By the law of uniform triangles: The relationship between contact force and tension is equal to the relationship between distortion and new length.

$$\frac{W}{T} = \frac{d}{L_2} \rightarrow d = \frac{WL_2}{T} \qquad (3)$$

$$(1)+(2)+(3)$$

$$S + \frac{L_0(T - T_0)}{EA} = \sqrt{S^2 + \left(\frac{W}{T}\left(S + \frac{L_0(T - T_0)}{EA}\right)\right)^2}$$

This equation is solved for each given span. For each span, there is a tension solving the equation.

APPENDIX V – SPECIFICATION OF DEMANDS

Chalmers		**Document type** ***Project***	**Specification of demands** Trawl wire abrasion testing apparatus
Utfärdare: Peter Sörensen			***Skapad:*** 2013-02-06 ***Modified: 2013-04-16***
	Criteria		***Goal value:***
	Function		
		Provide accurate specific testing data	
1.	**Performance**		
	1.1	Be a scale model	By a factor X of full size test
	1.2	Apply abrasion	By 32 mm * X steel wire, same type as trawlers u
	1.3	Apply abrasion	Reflecting 400 m steel cable, single direction
	1.4	Apply contact force	0 – 45 kN * X
	1.5	Allow reading of data	Contact force
	1.6	Allow reading of data	Wire speed
	1.7	Allow reading of data	Wire angle
	1.8	Allow reading of data	Wire distance traveled
	1.9	Allow reading of data	Wire tension
	1.10	Sample compatibility	Let a sample of 254-284 mm fit in testing spot
	1.11	Allow evaluation of sample	Ocular inspection
	1.12	Consistent results	90% error margin
	1.13	Apply same or higher testing forces	than specified in testing
	1.14	Minimize set-up time	Maximum 1 h from set-up to start of test
	1.15	Supply ecological validity	North sea
	1.16	Allow reading of cooling	Temperature of water
	1.17	Supply wire propulsion	146 kN * X, 4.5 knots (2.3 m/s)
2.	**Longevity**		
	2.1	Longevity	5 years
	2.2	Longevity	10 years
	2.3	Resistance to corrosion	Minimum 3 years before corrosion hinders use
	2.4		
3.	**Maintenance**		
	3.1	Allow cleaning	Withstand ordinary cleaning agents
	3.2	Allow exchanging of wire	Replacing a worn, dysfunctional or broken one
	3.3	Dirt repellent	
4.	**Manufacturing costs**		
	4.1	Manufacturing cost	At most 200000 SEK
5.	**Manufacturing volume**		
	5.1	Production volume	1-5 st
6.	**Size**		
	6.1	Maximum number of separate parts	10 st
	6.2	Transportable	By forklift
	6.3	Storage volume	Less than 1 cubic meter
	6.4	Withstand transportation	Transportation by car, truck, train or similar shou
7.	**Weight**		
	7.1	Weight	Less than 300 kg
	7.2	Low weight	Less than 100 kg
8.	**Aesthetics and design**		
	8.1	Express durability	90% of all engineers shall find it so
	8.2	Express functionality	90% of all engineers shall find it so
	8.3	Express reliability	90% of all engineers shall find it reliable
9.	**Material**		
	9.1	Made from existing material	
	9.2	Made from material and components deliverable by current contacts	
10.	**Patents and literature**		
	10.1	The product shall not interfere with existing patents	
11.	**Ergonomics**		
	11.1	Allow good physical ergonomics	
	11.2	Allow good cognitive ergonomics	Negligible margin for human error
	11.3	Minimize learnability effort	Correct use after 1 trial
	11.4	Be safe	Hinder access to dangerous areas and protect a

	D/W	Weight	Method of verification	Referens (kravställare)
	D			Calora
	W	5	Measurement	Calora
use	D		Functional use	Statoil
	D		Measurement	Statoil
	D		Measurement	Statoil
	D		Obvious	Project Group
	D		Obvious	Statoil
	W	2	Obvious	Project Group
	D		Obvious	Statoil
	D		Obvious	Statoil
	D		Functional use	Calora
	D		Obvious	Calora
	D		Several test comparisons	Project Group
	D		Measurement	Statoil
	W	4	Measurement	Project Group
	D		Measurement	Calora
	D		Measurement	Project Group
	D		Measurement	Statoil
	D		Use	Project Group
	W	3	Use	Project Group
	D		Theoretical evaluation	Project Group
	D		Functional use	Project Group
	D		Exchange of wire	Project Group
	W	3	Remain clean through use	Project Group
	W	4	Part index, actual cost	Calora
	D		Obvious	Calora
	D		Obvious	Project Group
	W	5	Obvious	Calora
	W	5	Obvious	Project Group
ld have no effect on	D		Functional use	Project Group
	D		Estimation, weight	Project Group
	W	3	Estimation, weight	Project Group
	W	4	Interviews	Project Group
	W	3		Project Group
	D		Interviews	Project Group
	D		Catalog search	Project Group
	W	5	Obvious	Project Group
	D		Patent search	Project Group
	W	3	REBA evaluation	Project Group
	W	2	PHEA evaluation	Project Group
	W	4		Project Group
gainst structural failu	D		It doesn’t cause bodily harm	Project Group

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