CHALMERS

Development of Overhead Launch and Recovery System

DOMINIK BÜCHEL

NICKLAS ÅKERLUND

Department of Shipping and Marine Technology
Division of Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS IN THE INTERNATIONAL MASTER'S PROGRAMME IN
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Cover:
View of the overhead Launch And Recovery System mounted on the hangar of the reference vessel.

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ABSTRACT

A market demand for a launch and recovery system for remotely operated vehicles, ROV, is identified and current thesis describes the development of a conceptual system, involving both concept generation as well as verification with calculations. The suggested solution operates the remotely operated vehicle from the hangar of the vessel, out over the ship side, lowering it to the operational depth and then recovers it back into the hangar.

Launch and recovery systems must be adaptable to a wide variety of vessels and the environment is different on each vessel. A calculation tool is presented that can quickly give the main dimensions of a product at an early stage of the development process. This tool that makes it possible to input the build-in dimensions of the system and the desired classification society. The tool gives the main dimensions such as the size, weight, hydraulic cylinder dimensions and reaction forces. Secondary output such as relative positions of cylinder attachment points etc. is also available.

Calculations are primarily made in MATLAB, and geometric models are created in Autodesk Inventor. To provide an easy way of inputting variable parameters, an input sheet is constructed in Microsoft Excel.

The developed concept in combination with the calculation tool provides a concept that can be installed on a wide variety of vessels by only changing a small number of input variables.

Key words: LARS, ROV, ROV handling system, supply vessel equipment

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Preface

This thesis is a part of the requirements for the master's degree in Naval Architecture and Ocean Engineering at Chalmers University of Technology, Gothenburg, and has been carried out at the Division of Marine Technology, Department of Shipping and Marine Technology, Chalmers University of Technology between January and June of 2015.

We would like to acknowledge and thank our examiner and supervisor, Per Hogström, and our supervisor at TTS Ships Equipment, Adam Bengtsson, for their invaluable input and support throughout the work with this thesis. Further we would like to thank Kristoffer Bång and Javier Beltran for all the help we got during our time in Bergen. We would also like to express our appreciation to the team at TTS Ships Equipment for making our time there so pleasant.

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Dominik Büchel

Nicklas Åkerlund

Notations and Abbreviations

AOPS – Automatic Overload Protection System

AHC – Active Heave Compensation

C_l – Coefficient depending on stiffness of crane under consideration

DNV – Det Norske Veritas

F_d – duty factor

F_h – hoisting factor

LARS – Launch and Recovery System

L_1 – Live load

L_g – Dead load

L_{h1} – Horizontal component of live load due to heel and trim

L_{h2} – Next most unfavourable horizontal load (usually due to slewing acceleration)

L_{h3} – Horizontal component of dead load due to heel and trim

L_w – The most unfavourable wind load

LR – Lloyd's Register

MOPS – Manual Overload Protection System

ROV – Remotely Operated Vehicle

S_G – Dead weight of components

S_H – Horizontal forces/loads on the system

S_L – Working load

S_M – Inertia forces due to motion of the vessel on which the crane is mounted

S_w – Operational wind force

$S_{w,max}$ – Out of service wind force

SWL – Safe Working Load

TMS – Tether Management System

V_h – Hoisting speed

1 Introduction

This report describes the process of developing a new concept of a Launch and Recovery System, LARS, including strength calculations. In this introduction chapter, the background of the project is described as well as the purpose and limitations. The limitations are established to ensure that the project does not exceed the timeframe. This project is carried out in cooperation with TTS Ships Equipment AS in Bergen, Norway.

1.1 Background

Remotely Operated Vehicles (ROV's) are widely used within the offshore industry for tasks such as inspection, installation and maintenance of subsea structures. The increased usage of ROV's as a complement or substitute to saturation divers decreases the risk of incidents resulting in human casualties. Since the trend within the offshore industry points towards greater operational depths, the possibility to use divers is declining and the ROV usage becomes even more important. At the moment, ROV's are operating down to a maximum depth of 4200 m which is far beyond the limits for any divers, Comex S.A (2004).

For all products operating within the offshore industry, operability and reliability is of extremely high importance since downtime is very expensive and external conditions can be rough. This exposes not only the ROV for great challenges, but also the handling system must be able to perform its tasks during harsh conditions. As the exploration of new oil- and gas fields continues further north, the extreme arctic conditions introduce even more severe environmental loads on all systems, including the LARS. Since the economic margins decrease in the industry, Lunan, D. (2015), and the competition grows stronger, avoiding downtime becomes crucial for economically sustainable operations.

A launch and recovery system performs the task of moving the ROV from the deck of the mother ship, lowering it into the sea and then winching out the umbilical cable that supplies the ROV with power and communication from the surface. When the ROV has performed its task, the LARS winches it back to the surface and lifts it up onto deck. In addition to the ROV, a Tether Management System, TMS, and a wide variety of tools and material shall be able to be lifted with the LARS. In order to be able to operate in rough seas, motions of the vessel need to be compensated for by the system.

The starting point for this project is a demand for a LARS that does not occupy any deck area inside the ROV hangar of the vessel. TTS Ships Equipment does not have such a product at the moment and this would complete the product range in a very competitive way.

1.2 Objective

This master thesis report intends to go through the steps in the development of an overhead LARS for TTS Ships Equipment.

The objective of the master thesis is to develop deeper knowledge in generating concepts for new projects, get further understanding of class rules and how to apply them in different areas of work in the design of a LARS structure. In addition, providing an overhead LARS concept for further development.

A calculation tool for dimensioning the concept is also developed. This tool is flexible in order to fit a wide variety of vessels.

1.3 Methodology

The work process is divided into separate sections, each requiring different skill sets, methods, and software to complete;

- A reference vessel is chosen in order to identify important information
- Concept generation – The task is to generate a new concept for TTS Ships Equipment using a systems engineering approach. By using existing solutions along with new ideas, new concepts are generated and evaluated with different tools
- Calculation tool – After evaluating the geometry for the generated concept, the tools required to perform strength analysis and calculate dimensions are developed in MATLAB based on beam bending theory as well as class rules
- Visual tools – Autodesk Inventor is used to visualize the geometry of the final concept

1.4 Limitations

To fit the timeframe, it is crucial to focus on the essential parts and to have clear limitations. The major focus is to generate a design that performs designated tasks in a way that gives a maximum customer value. There are several alternative solutions and room for optimization of the design in the end of this project. This project does not intend to follow the design all the way to a finished product, but instead focus on the structural design.

There are several classification societies that offer class approval for launch and recovery systems. For this project, Det Norske Veritas, DNV, and Lloyd's Register, LR, are considered since these are most frequently used and requested by the customers of TTS Ships Equipment, DNV (2013) and LR (2013). The differences between societies are not very significant in this field and therefore the design can be modified at a later stage to fulfil the demands of other classification societies.

The chosen vessel is a regular supply vessel with known dimensions, such as height over sea level from hangar deck, hangar opening dimensions, and hangar dimensions.

The chosen concept includes existing products from the TTS Ships Equipment product range; these are not considered in detail but rather defined in terms of interface dimensions and loads caused by the LARS acting on them. An example of this is the side hinged doors that are mounted in the lower part of the hangar opening. The outer dimensions of these are calculated but the detailed designs of them are left out of this project.

There is another LARS development project on-going within TTS Ships Equipment that has developed a snubber that connects the crane and the ROV. Instead of reinventing the wheel, this design is incorporated into this project as well.

Fatigue calculations are dependent on notch factors to be known and accurate and since this demand a lot of detailed design work this is left for future work.

Control systems and software are not considered in this report. This is a very important part of the design but demands a whole other set of competence than the structural design and is therefore left for future work. Classification societies have a large number of software related safety features such as Automatic Overload Protection System, AOPS, and Manual Overload Protection System, MOPS, to reduce the risk of structural damage due to overloading. These are examples that will need to be implemented to a finished product, but not considered in this project.

Another important part of the development process that is not covered is the selection of winch for the system. An Active Heave Compensated winch, AHC-winch, with capacity for 3000 – 4000 m of umbilical cable is required. There are on-going development projects of suitable winches within the TTS Group, but as they are still being developed, this is left for future work.

ROV's are connected to the ship through an umbilical cable that both transfers power and communication and works as a lifting cable. Umbilical cables are different depending on a number of factors such as ROV-type, working conditions, depth etc. Therefore, a structural consideration such as the stiffness of the cable is assumed based on a worst case selection of data from several different manufacturers. No further modelling of the umbilical cable is carried out.

A CAD-model of the design is generated and will only be used for visualisation of the solution as no commercial FEM software will be used.

Even though the focus of the project is to develop and dimension the structure according to the rules of the classification societies, the project does not cover a complete class approval. This is considered to cover too many areas that are outside the scope of the project and will also demand an economic effort from TTS Ships Equipment.

2 Concept generation

The goal of the concept generation is to generate as many different solutions as possible and then narrow them down to one or two solutions that are taken further in the development process. This is to investigate as many solutions as possible and to make sure that the final concept is as good as possible. Two concept generating tools such as a morphologic matrix, Silverstein et al. (2009), and a weighted evaluation matrix are used to find possible solutions. These tools are described further in this chapter, along with some concepts and eventually the final concept.

2.1 Functional analysis

In order to generate new concepts using different matrices, some solutions first have to be defined. A number of solutions from competitors are inspected to get inspiration, as well as existing solutions from TTS Ships Equipment. The operation of the LARS is divided into different parts and requires different solutions.

The operation is divided into the following functions:

- Openings – type of hangar opening, i.e. top hinged door, side hinged doors etc.
- Lifting operation from deck – there are a few possibilities to alter the lifting operation
- Manoeuvring ROV over board
- Lowering operation – There are different ways of getting the ROV safely in the water, it can be lowered freely or in a controlled motion
- Closing door – to close the door during operation will serve as weather protection inside the hangar. The crew can work inside the hangar in bad weather and it also prevents people falling overboard

Table 2-1 shows how the results from the functional analysis are placed in the morphological matrix. The first row contains the functions listed above and each column contains the possible solutions identified for every function.

Table 2-1 Identified function analysis

Openings	Lifting operation from deck	Maneuvering ROV over board	Lowering operation	Closing door/hatch
Top hinged door	Fixture already mounted on overhead rail	Move fixture on OH rails	Rails along hull for vertical movement through splash-zone	Side hinged door(s)
Top hinged door with arm(s) for ROV	Slide/push on floor	Move along OH rail	Lower freely	Vertically sliding door
Side hinged door(s)	Winch it from the floor to hang from OH rail	Telescopic OH rail	Fold out arm from door	Vertically sliding door with cutout
Side hinged door(s) with cutout	Hydraulic snubber manoeuvring	OH A-frame	Guiding axis with hull support	Horizontally sliding door
Vertical sliding door		Fold out arm for more outreach		Horizontally sliding door with cutout
Horizontally sliding door		Rails on top hinged door		Close lower door(s)
Outward opening		Rails on side hinged door(s)		Close side door(s)
Inward opening/inward roller gate (can't be used, we do not have a free hangar roof)				Endfitting on telescoping beam

2.2 Demands and preferences

During discussions with experts at TTS Ships Equipment, along with the studies of existing solutions, some demands and preferences are identified. Many of these demands go hand in hand, e.g. if the ROV is to be lowered freely, a minimum outreach of the crane has to be specified in order to keep the umbilical cable at a safe distance from the hull.

How far the system can reach inside the hangar is also important. During maintenance of ROV and TMS, it is preferable to be able to place them separately using the crane only, avoiding extra equipment inside the hangar.

The weight of the LARS is important in several aspects. A lighter solution means less material cost, and also requires less strengthening of the structure around the door and attachment points.

The interface between doors and the LARS is important but not crucial. Creating a solution that incorporates both results in a product that is more appealing to customers. It is also easier to arrange the solution in a way that will ensure weather protection in the hangar during operations, i.e. closing the hangar doors when the ROV is lowered.

Having an overhead system means a cleaner floor inside the hangar. For these types of cranes the structure is arranged on the hangar walls and roof instead, leaving more space on the hangar floor for maintenance and equipment storage.

Here is a list of the demands that were identified:
- Outreach
- Inreach
- Weight
- Interface
- Overhead system

2.3 Concept generation

A system engineering approach to generate concepts is used. Instead of coming up with an idea one by one, a strategy to use known methods and create as many concepts as possible is used. This section describes how existing solutions and new ideas are put together and evaluated according to the demands and preferences.

2.3.1 Morphologic matrix

A morphological matrix is a powerful tool to use when generating new concepts, Silverstein et al. (2009). The idea is to have a basic understanding of what the final product is supposed to do, but not knowing how to get there. The parameters described in the functional analysis are used to form the top row in a matrix. In each column the different solutions found during the pre-study are placed. Concepts are now generated by linking the different solutions together, as can be seen in Figure 2-1.

Openings	Lifting operation from deck	Maneuvering ROV over board	Lowering operation	Closing door/hatch
Top hinged door	Fixture already mounted on overhead rail (ref. Ulmatex OH LARS)	Move fixture on OH rails	Rails along hull for vertical movement through splash-zone	Side hinged door(s)
Top hinged door with arm(s) for ROV	Slide/push on floor	Move along OH rail	Lower freely	Vertically sliding door
Side hinged door(s)	Winch it from the floor to hang from OH rail	Telescopic OH rail	Fold out arm from door	Vertically sliding door with cutout
Side hinged door(s) with cutout	Hydraulic snubber manoeuvring	OH A-frame	Guiding axis with hull support	Horizontally sliding door
Vertical sliding door		Fold out arm for more outreach		Horizontally sliding door with cutout
Horizontally sliding door		Rails on top hinged door		Close lower door(s)
Outward opening		Rails on side hinged door(s)		Close side door(s)
Inward opening/inward roller gate (can't be used, we do not have a free hangar roof)				Endfitting on telescoping beam

Figure 2-1 - Example of concept generation using a morphologic matrix

Following the red arrow in the morphologic matrix results in the following concept;

1. Vertically sliding door
2. Fixture already mounted on overhead rail
3. Moving the fixture on overhead rails
4. Rails along hull for vertical movement through splash-zone
5. Vertically sliding door

The number in the list above represents the columns in the morphologic matrix. A grand total of 23 concepts are first generated using the morphologic matrix, but as this is too many concepts to evaluate further, a very simple weighting evaluation is performed. Each concept is rated from 1-5 from two aspects and a mean value is calculated. The concepts with a mean value of over 3.5 are taken further in the evaluation process, resulting in nine concepts left for further consideration. The value 3.5 is chosen as it provides a reasonable number of concepts for further evaluation.

2.3.2 Weighted evaluation matrix

A weighted evaluation matrix is used to select which of the nine concepts to work further on. Assigning weights to the demands and preferences with a value according to their importance, an ideal solution is established with the highest possible score for comparison. Each concept is given scores for all demands respectively, which is multiplied by the weight and finally added up to a total value. The total value of each concept is then compared to the total score of the ideal solution.

Table 2-2 shows a small cut-out with some examples from the weighted evaluation matrix. In the first column a number of parameters that are important for the final concept are presented. The second two columns represent an ideal solution with the highest possible score. The "Weight" column is given a value depending on how important the parameter is for the final solution, which is then multiplied with five, giving the highest "Score" for the ideal solution.

Every concept is then given a value for each parameter based on how good its solution is, which is multiplied by the ideal weight. The total score of each concept is then compared to the total score of the ideal solution. For example Concept N 8 in the table only receives a total score of 0.62 compared to Concept N 5 on 0.97. This evaluation resulted in five concepts presented at TTS Ships Equipment for discussion.

Table 2-2 Cut-out of the weighted evaluation matrix

	Weight	Score	Concept 12		Concept N 8		Concept 5		Concept N 5	
Outreach	4	20	5	20	3	12	4	16	5	20
"Inreach"	4	20	5	20	2	8	5	20	5	20
Complicity	5	25	5	25	3	15	4	20	5	25
Interface LARS/Door	4	20	4	16	4	16	4	16	5	20
Maintenance	5	25	4	20	3	15	4	20	4	20
Handling	5	25	2	10	3	15	5	25	5	25
Closing door	3	15	5	15	4	12	4	12	5	15
	4	20	5	20	3	12	5	20	5	20
	Total	205		181		128		184		200
		1		**0,88**		0,62		**0,89**		**0,97**

The full evaluation matrix, including concept descriptions, can be seen in Appendix B.

2.3.3 Concept evaluation

The five concepts left after the matrix evaluation were presented to TTS expert, G. Soltveit (2015, January 28), for evaluation and discussion. Following is a short description of the generated concepts:

1. Vertical sliding door, winch ROV from floor to hang from overhead rail, telescopic overhead rail, lower freely, vertical sliding door with cut-out
2. Side hinged doors, winch ROV from floor to hang from overhead rail, telescopic overhead rail, rails along hull for vertical movement through splash-zone, side hinged doors
3. Telescoping door, winch ROV from floor to hang from overhead rail, telescopic overhead rail, rails along hull for vertical movement through splash-zone, horizontally sliding door
4. Top hinged door with rails, winch ROV from floor to hang from overhead rail, rails on top hinged door, rails along hull for vertical movement through splash-zone, vertically sliding door
5. Vertical sliding door, winch ROV from floor to hang from overhead rail, telescopic overhead rail, rails along hull for vertical movement through splash-zone, vertically sliding door with cut-out

As can be seen, the concepts are quite similar with only a few changes. During the concept evaluation several crucial points were established. To have rails along the hull is an expensive and complex solution, it requires an irregular hull structure which results in extra operational costs, i.e. increased fuel consumption and wear and tear of fenders in port. If rails are to be used along the hull, the ROV has to be lifted on a fixture that aligns perfectly with the rails. The fixture itself will also require space inside the hangar and all together, it was established that rails along the hull is a too complicated solution for this project.

The weighted evaluation matrix is based on estimations for each parameter, where the weight of the parameter is chosen according to how important it seems to the final concept. At these early stages of the project, the experience to perform such estimations is not established yet. This is the reason why the interview with TTS expert led to the disregarding of the five concepts.

2.3.4 New concepts

After discussing the generated concepts, new ideas started to take shape. Details that primarily had been considered as good solutions were re-evaluated according to some very good input. Two new solutions are developed by removing the rails in the hull and focusing on sufficient outreach instead of a guided lowering operation. Compact size when not in use and ability to close the hangar opening as much as possible are important parameters that formed the two final concepts. The two final concepts are presented in Figure 2-2 and are described further in the coming sections. The yellow box represents the ROV and the grey cylinder represents the TMS.
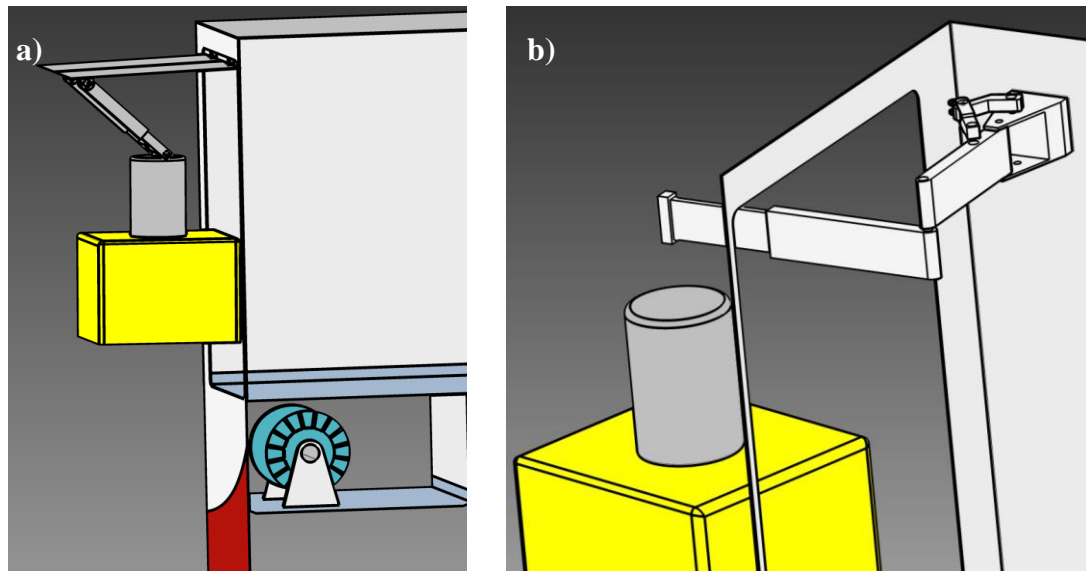

Figure 2-2 a) side view of concept one. b) rear view of concept two.

2.3.5 Evaluation of concept one

Concept one integrates a top hinged hangar door with a telescopic A-frame to form a knuckle boom crane as seen in Figure 2-2 a). The idea of having a telescopic crane is to generate sufficient reach both out from the ship side and also into the hangar. This makes it possible to lower the ROV without any rails in the hull since it is far away enough not to hit the ship side. It also makes it possible to place the ROV and TMS separately inside the hangar, which is beneficial out of maintenance point of view.

The integration with the top hinged door makes it a very compact design and does not occupy any deck area. In combination with side hinged hangar doors the solution offers the possibility of closing a large part of the hangar opening during operation which is also desirable. By having the A-frame attached to the door it is integrated with other TTS-products, making it possible to sell a whole package of hangar equipment instead of just the launch and recovery system.

The top hinged door is moved from the closed (vertical) position to the fully opened (horizontal) position by a set of hydraulic cylinders fixed to the hangar wall. This part can be considered as the crane boom when referring to this LARS as a knuckle boom crane. An A–frame is connected to the top hinged door with two hinges and a set of hydraulic cylinders to control the angle between the door and A-frame. The A-frame has a telescopic part that is controlled by a set of hydraulic cylinders. This telescope is used to get extra outreach in the launch position and also makes it possible to put down the ROV and TMS separately inside the hangar.

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2.3.6 Evaluation of concept two

The second concept consists of a knuckle boom crane mounted on the hangar wall, as can be seen in Figure 2-2 b), making it possible to move the ROV in the horizontal plane only. Vertical movement inside the hangar is achieved by using the umbilical winch. Hydraulic cylinders or motors control the motion of the arm and when it is not in use it folds together into a small package along the hangar wall. The out- and in-reach of this solution is very good due to the freedom of movement in the horizontal plane in combination with the telescopic jib.

This concept is depending on the possibility to use hydraulic turning motors to control the motion of the jib position in relation to the boom position. This solution requires heavy components located far out on the crane, resulting in large moments due to the own weight of the structure that needs to be distributed in the hangar wall attachment. The hydraulic motors will also need to withstand the horizontal force component of the umbilical cable, which will be significant.

The reaction forces from concept two will demand much strengthening of the hangar wall and will make the design much less compact.

2.4 Concept selection

Concept one is easier to design from a structural point of view since the geometry gives rise to smaller reaction forces that are distributed in a better way than for concept two. This reduces the impact on the surrounding ship structure which is appreciated from both the customer and the shipyard. The reaction forces from concept two demands much strengthening of the hangar wall and makes the design much less compact.

For operations within the hangar it is beneficial not having to use the umbilical winch to lower the ROV to the floor. This increases the safety in the hangar since the ROV is not able to swing freely when being lowered to the floor but is instead fixed to the crane jib during the lowering. In rough sea states this makes a significant difference to the working environment and decreases the risk of damage to both humans and equipment.

The horizontal layout of concept two gives rise to large moments in the hinges between the boom and jib, and between the boom and the wall attachment. For a normal knuckle boom crane these moments are taken up by the hydraulic cylinders which are loaded in their axial direction. Concept one gives a much more beneficial loading situation in this case. This problem can be solved with large slewing bearings, but they will be heavy, expensive, and highly loaded. Another solution is to design hinges and cylinders that can control the motion in the same way, but this is a more complex and space demanding solution that is not considered to be better than concept one.

After the discussions and general consideration it is decided that the benefits of concept one are greater than the benefits of concept two.

3 Class rules

Equipment designed for the offshore industry is often expensive and operates in harsh conditions. Equipment failure is disastrous in many ways, not least economically. Hence, all equipment needs to be insured to limit the economic effect of failures. In order for an operator to be able to insure the equipment a classification society must approve the design for the operational conditions.

There are a number of classification societies that offer services within the offshore industry, two of them are DNV and LR. Both of these two have their own rules for approval of lifting appliances which differ slightly. DNV and LR are chosen since these are the two most frequently used classification societies for the customers of TTS Ships Equipment.

The applicable rules from both classification societies are presented and discussed in the following sections. A comparison of the major differences is presented at the end of this chapter.

3.1 DNV – Applicable rules for LARS

The specific regulations regarding launch and recovery systems for ROV's are short and concise, referring to the regulations regarding offshore cranes, DNV (2013, a). Some rules regarding safety details are also found in the section for shipboard cranes DNV (2013, b).

3.1.1 Basic requirements

Basic requirements consider rules such as choice of material and welding procedures etc. These requirements are described in DNV (2013, c). For the selection of material a design temperature of -20 ^{o}C is chosen in accordance with recommendations from DNV (2013, f) for offshore cranes. The selection is then based on this temperature and the needed strength from the strength calculations. DNV (2015) contains definitions of steel grades with different mechanical properties that can be used.

3.1.2 Loads on LARS

This section describes the loads that need to be considered for a LARS. One major part of this is to determine the dynamic factor that the static load is to be multiplied by to compensate for the motions of the ship and the load during the lifting operation. The dynamic factor also considers the interaction between the suspended load and the waves on the sea surface. The zone where the suspended load is subjected to wave interaction is called "splash zone" and give rise to the worst loading of the entire operational cycle. In order to obtain a general solution to implement on a wide variety of vessels, the dynamic factor is assumed to be equal to three. This is a general and commonly used way of obtaining a product that is not designed for one ship only. The operator is then able to calculate the operating limit for the system knowing all of the motion parameters of the vessel at different sea states and the dynamic factor that the system has been designed to withstand.

3.1.2.1 Principal loads

These are loads due to the dead weight of components, loads due to the working load and loads due to pre-stressing, DNV (2013,e).

3.1.2.2 Vertical loads

Vertical loads on the structure are calculated by multiplying the working load with the dynamic factor. As mentioned earlier the dynamic factor is assumed to be equal to three. The vertical load does also consist of the dead weight of the components; i.e. the loads due to the weight of the crane itself.

3.1.2.3 Horizontal loads

Lateral (side lead) and radial (off lead) forces are calculated according to DNV (2013, a). Radial force is calculated both at lift-off and when the load is airborne and the larger one is then used for design purpose. The horizontal loads are calculated as the resulting forces of lateral and radial forces as well as the horizontal components of the vertical loads. These horizontal forces due to the vertical loads are calculated by projecting the vertical loads on the horizontal plane by the heel and trim angles. In the regulations, distance from the crane-tip to the supply vessel deck is needed for the calculations. This distance is interpreted as the distance to the water surface since it is from here that the ROV is lifted. Normally offshore cranes operate between an offshore platform and a vessel; this is why this formulation is used in the rules.

3.1.2.4 Wind loads

Wind loads are calculated according to DNV (2013, d), considering the crane, snubber and the ROV. The wind speed is the recommended design wind speed for "offshore and open areas", 24 m/s, and the "out of service wind speed" is 44 m/s according to DNV (2013, d).

3.1.2.5 Motions of the vessel

For this part the DNV – document "Rules for Classification of ships" (Pt.3, Ch.1, Sec.4) "Ship Motions and Accelerations" is to be considered. However, since the calculations according to "Ship Motions and Accelerations" demands a lot of vessel specific input data, these motions are not considered. The loads due to these motions will only affect load case 3b, defined in Section 3.1.4.3, which is when the crane is not in service. Hence, this load case will probably not be the most severe one.

3.1.2.6 Snow and ice

Loads due to snow and ice are not considered since the crane is not particularly sensitive to such effects and is not considered to operate under exceptional conditions according to DNV (2013, e)

3.1.2.7 Temperature variations

Only needs to be considered in special cases, and this is not considered to be a special case.

3.1.3 Practical aspects of applying the rules

An issue with applying the DNV rules for calculation of off lead forces is that they are developed for cranes mounted on platforms high above the sea surface. A typical height above the sea surface can then be 30 m, which is much higher than if the crane is mounted on a ship. LR gives a fixed angle to use to project the vertical load to the horizontal plane and this angle for significant wave height of 5 m is 10°. The maximum heel angle is then added to this in order to calculate the worst case of loading. DNV uses a horizontal distance depending on the significant wave height, and the vertical distance from the sea surface to the crane tip to achieve the same effect.

For cranes mounted relatively close to the sea surface the off lead force is very large using this method. To compare, the angle corresponding to the off lead angle from LR calculated for a crane located 14 m above the sea surface gives an angle of 35° instead of 10°. This is not reasonable so instead an off lead angle of 20° is deemed sufficient to calculate the DNV off lead force. This represents the worst case of loading as a result of maximum heel and maximum off lead motion of the load. Rotational speed is set to zero since the considered concept does not have the possibility to rotate the load around the vertical axis.

Horizontal loads due to the inertia forces of the system are to be considered if the effect is significant. In this case the operational accelerations are very low; hence the effects of these are not considered to be significant and therefore disregarded.

3.1.4 Load case definitions

There are four load cases taken into consideration for this application, where load case two is the most severe case.

3.1.4.1 Load case 1 – Crane working without wind

The first load case contains the deadweight of the components, the working load and the horizontal loads. Deadweight is the load from the mass of the crane, working load is the load from the lifted object (ROV and possibly TMS) and weight of the cable that is hanging from the crane. Horizontal loads are described in Section 3.1.2.3. Heel and trim angles are found in DNV (2013, d).

Load case 1 (DNV Lifting Appliances, Ch. 2, Section 2.2):

$$S_G + S_L\psi + S_H \qquad \text{Eq. 3.1}$$

Where S_G is the dead weight of components, S_L is the working load, ψ is the dynamic factor, and S_H is the horizontal forces on the system.

3.1.4.2 Load case 2 – Crane working with wind

This is almost the same as load case 1 but the wind load is added and the horizontal components are based on heel and trim angles that are 1.5 times larger than those in load case 1 DNV (2013, d). See 3.1.2.4 for wind load calculations.

Load case 2 (DNV Lifting Appliances, Ch. 2, Section 2.3):

$$S_G + S_L\psi + S_H + S_W \qquad \text{Eq. 3.2}$$

Where S_G is the dead weight of components, S_L is the working load, ψ is the dynamic factor, S_H is the horizontal forces on the system, and S_W is the operational wind force.

3.1.4.3 Load case 3 – Crane subjected to exceptional loading

Load case 3 consists of two combinations which are applied if the crane is subjected to exceptional loads. Case 3a is not applicable to the LARS since it considers buffer loads as an exceptional load. Case 3b on the other hand considers inertia forces due to motion of the vessel on which the crane is mounted and out-of-service wind. If the LARS is mounted outside the hangar, the out-of-service wind load has to be considered. This load case is considering loads when the crane is not in use.

Load case 3b (DNV Lifting Appliances, Ch. 2, Section 2.4):

$$S_G + S_M + S_{W,max} \hspace{3cm} \text{Eq. 3.3}$$

Where S_G is the dead weight of components, S_M inertia forces due to motion of the vessel on which the crane is mounted, and $S_{W,max}$ is the out of service wind force.

3.1.4.4 Latched load case

For the condition where the ROV has been connected to the snubber and the crane moves the ROV inside the hangar, a dynamic factor of 1.3 is used instead of 3 according to the DNV recommendations for shipboard cranes. This is due to the fact that the lifting operation in this case does not have to encounter wave interaction and the motions of the load are very restricted.

3.1.5 Structural strength

The strength calculations should consider excessive yielding, buckling and fatigue fracture for the most unfavourable position of the load and for all applicable load cases. For the excessive yielding evaluation, the critical stresses for each load case are calculated with material data and tabulated safety factors from DNV (2013, e). The critical yield strength is compared with the calculated stress in each element.

Safety factors against buckling are tabulated for the three load cases in DNV (2013, e). Critical buckling loads should be calculated according to recognized methods and then be multiplied by the tabulated safety factors. Calculation of critical buckling load for the cylinders is performed according to DNV (1999) and cylinder dimensions are increased until the required safety factor is obtained. This method allows for a buckling safety factor of 2.3 for load case two, which is the critical load case.

For the fatigue assessment, DNV (2013,e) recommends the procedure described in DNV-GL (2014) or equivalent standards for cranes. The calculations should consider material and notch factor, component group, fluctuating factor and if the maximum stress is in tension or compression. The calculations are intended to give the critical amplitude for fluctuating or alternating load. Since these calculations need a very detailed design, this is left for future work. See Section 1.4.

3.1.6 Load chart

A load chart or table shall be available at operating stand DNV (2013, a). Load charts are produced as a part of the structural design and used for dimensioning the system. A specific load chart for the operating stand is regarded as a detail for further work.

3.2 Lloyd's register – Offshore cranes

Lloyd's Registers regulations regarding Launch and Recovery Systems go under the section for Submersible Handling Systems, covering launch and recovery of manned and unmanned submersibles in an open sea environment. The design requirements from the section of Shipboard Cranes are also applicable for submersible handling systems, LR (2013, a).

The choice of material is to comply with LR's requirements for hull structural steel, LR (2014).

3.2.1 Loads on LARS

This section describes the loads, forces, and factors that need to be taken into consideration for a launch and recovery system classed by the standards of LR.

3.2.1.1 Factored load

The factored load is considered to act on the LARS for the purpose of designing the component parts. It consists of the live load multiplied by factors to ensure that the design is able to hold the loads that might occur.

3.2.1.2 Duty factor

The duty factor for all submersible handling systems is set to 1.20, LR (2013 b). The sums of all static and dynamic loads are to be multiplied by the duty factor to give the factored load.

3.2.1.3 Horizontal loads

Several loads are taken into consideration when calculating the horizontal loads. The live load is the sum of the safe working load and the static weight of any components which are directly connected to and undergo the same motion as the safe working load during the lifting operation, i.e. the maximum in-air weight of the submersible and the weight of the hoisting cable. If the maximum weight of the hoisting rope combined with the in-water weight of the submersible is greater than the in-air weight, this weight is to be considered as the live load.

The dead load is the own-weight of any component of the lifting appliance, not included in the live load.

The horizontal component of the live load is based on loads acting on the submersible during roll and pitch, expressed as static angles of heel and trim.

3.2.1.4 Dynamic forces

Dynamic forces due to hoisting are forces acting on the structure when the submersible is accelerated during lifting operations. This effect is given by multiplying the live load by a hoisting factor, which is calculated from the hoisting speed and a coefficient depending on the stiffness of the crane, LR (2013 d).

The hoisting factor can also be based on accelerations from the mother ship's behaviour, taking into account the ship's headings and sea conditions.

Tabulated values of the hoisting factor also exist for different sea states, LR (2013 c). As the maximum significant wave height in this project is set to 5, the hoisting factor is equal to 2.5.

3.2.2 Load combinations

There are four load cases defined for offshore cranes and load case two is the most severe one for this project.

3.2.2.1 Case 1 – Crane operating without wind

When the crane is operating without wind the design is to be considered with respect to a combination of dead load, live load and horizontal forces, given by the following equation (LR Lifting Appliances in a Marine Environment, ch. 4 sec. 2.15):

$$F_d\big(L_g + F_h(L_I + L_{h1}) + L_{h2} + L_{h3}\big) \qquad \text{Eq. 3.4}$$

Where F_d is the duty factor, F_h the hoisting factor, L_1 the live load, L_g the dead load, L_{h1} the horizontal component of live load, L_{h2} the next most unfavourable horizontal load, and L_{h3} the horizontal component of the dead load.

3.2.2.2 Case 2 – Crane operating with wind

If the crane is operating with wind, the most unfavourable wind load is added to the equation in Case 1 (LR Lifting Appliances in a Marine Environment, ch. 4 sec. 2.15):

$$F_d\big(L_g + F_h(L_I + L_{h1}) + L_{h2} + L_{h3}\big) + L_w \qquad \text{Eq. 3.5}$$

Where the variables are the same as in Case 1, with L_w which is the most unfavourable wind load.

3.2.2.3 Case 3 – Crane in stowed condition

The forces resulting from accelerations due to ship motions and static inclination, and wind forces acting on the crane in its stowed condition (LR Lifting Appliances in a Marine Environment, ch. 4 sec. 2.15).

3.2.2.4 Case 4 – Crane subjected to exceptional loading

Case 4 consists of three exceptional loading conditions, LR (2013, e):

a) Coming into contact with buffers – not applicable for this project
b) Failure of the hoist wire or sudden release of load for cranes with counterweight (F_h to be taken as -0.2)
c) Test loading

3.2.2.5 Latched load case

When the ROV is attached to the snubber, the hoisting factor will no longer be relevant. Hence, this is neglected for the load calculations when the crane operates with the ROV locked to the snubber.

3.3 Comparison of Class Rules

The rules from DNV and LR applicable to the design in this project are very similar; most calculations are the same with some change of notations. One major difference however is the calculation of the factor to be multiplied with the static load to obtain the dynamic loads on the structure. While LR relies on tabulated values for a given sea state and type of vessel, DNV focuses on giving a way of calculating the factor based on a large amount of input data.

There are pros and cons with both methods; LR gives a generally applicable way of obtaining the dynamic loads while the DNV method will give a factor specific for one vessel. When developing a product that is to be mounted on a wide variety of vessels, the method from LR is more convenient, but it does not offer the same freedom for optimization as the method from DNV offers.

The minimum dynamic factor allowed for design according to DNV is 1.3, which compared to LR's value 3 makes a large difference between the different rules. It may not be possible to obtain a dynamic factor as low as 1.3 but it implies that there is room for structural optimization.

Another difference is the procedure for calculating the horizontal forces acting on the structure. As described in Section 3.1.3, the method used by DNV to obtain these forces is not really applicable on cranes located close to the sea surface; hence an alternative procedure is applied. This is a well-known problem within TTS Ships Equipment and it was communicated at an early stage of the project.

In the end, the difference in applied load according to classification regulations is very small between LR and DNV. However, there are differences that do not directly affect the structural design such as requirements on safety equipment etc.
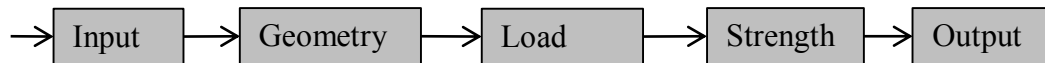
4 Calculations

A calculation tool to be used for dimensioning of different versions of the structure has been constructed in MATLAB. The tool consists of several script modules. In addition, an Excel-sheet is used to provide input dimensions to the calculation model. The sub-modules of the script and the content of these are presented in the following sections.

The flowchart below illustrates in which order the calculations are performed.

→ | Input | → | Geometry | → | Load | → | Strength | → | Output |

4.1 Input

To get a good overview of the parameters in the calculations, an Excel input is used to define parameters. This sheet gives the possibility to change the following:

1. Length of the hangar door
2. Height of hangar opening
3. Safe Working Load, SWL
4. Dynamic factor
5. Position of umbilical sheave inside hangar
6. Classification society

When the length of the hangar door is defined, cylinder attachment points and length of the A-frame are calculated directly in the Excel-sheet. These values are calculated as ratios that have been found by testing several different geometries and are shown directly in the Excel-sheet. All parameters are then passed on from Excel to MATLAB where the rest of the calculations are performed.

4.2 Geometry

As a starting point, dimensions are chosen to fit the reference vessel for the project. The dimensions are kept as variables in order to have total freedom of adapting the design for various vessels. In the geometry module, local dimensions are loaded from the Excel-sheet and global positions depending on the two basic angles and the length of the telescopic frame are calculated. Further, all angles used later on in the strength calculations, cylinder lengths, dimensions for calculating the loads according to classification rules, and the weight of the structure are calculated in this module.

Describing the geometry this way allows for using the data in several other subsequent calculations. It also provides a way of easily changing the dimensions or the position of the crane and then checks the clearance towards the hangar floor, doors and walls. This module also comes with a graphical interpretation of the operational cycle of the system, which shows the motions of the system relative to the vessel. This is primarily intended as a way of validating the geometrical calculations but it could, with some refinement, be used in an early stage of the construction of systems like this. The visualisation tool is also able to show nodal displacements, nodal forces and element forces due to an added load. This is also supposed to be a validation tool for the calculations but could be refined to be used in other areas if it is found relevant.

Figure 4-1 shows the graphical output of the geometric calculations. The thick arcs in the centre of the plot show the positions of the crane tip and the critical lower edge of the ROV during the operational cycle. In the left part of the picture there are two

rectangular objects with dashed line type, these represent the ROV and the TMS that are in the position where they are about to be lowered into the sea. The dashed line from the TMS represents the telescopic part of the A-frame and connects to the rest of the A-frame in its upper end. The rest of the A-frame is displayed with a thicker linewidth and connects to the side door and the hydraulic cylinder that control the angle between the A-frame and the side door. In the upper part of the picture there is a horizontal line that represents the side door. Since the parts that connect to the side door are connected by brackets on the outer surface of the door, there are vertical lines that represent these brackets. There are two thinner lines that connect to the side door brackets, these are hydraulic cylinders. The left one operates the A-frame in relation to the side door and the right one operates the side door in relation to the vessel. In the lower right corner there are two lines that represent the hangar floor and ship side.
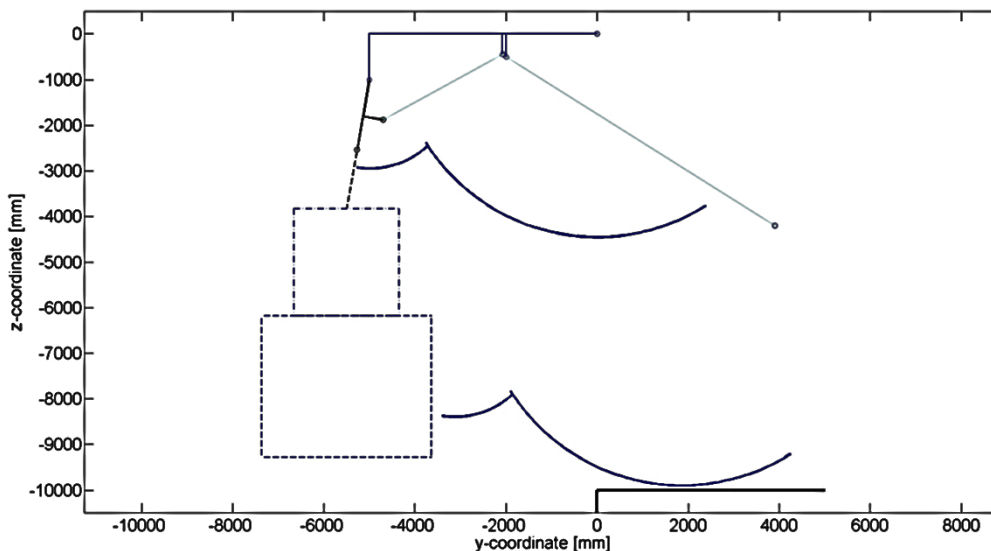

Figure 4-1 - Visualization of sweep movement of LARS and ROV

4.2.1 Geometric constraints

To be able to operate in a safe way, the ROV needs to be at a certain distance from the ship side during lowering. This distance depends on the distance between the crane tip and the sea surface as well as the operational sea state. The ROV must stay clear from the ship side during lowering, and in the reference case, a minimum outreach is defined as 5.5 m. Before the calculations proceed from the geometry module, this outreach is checked and if not fulfilled the calculations are aborted.

Hydraulic cylinders are used to control the position of the system and the stroke to minimum length ratio of these must be checked before the calculations move on. The stroke of a hydraulic cylinder is usually limited to about 70 % of the minimum length since a part of the rod has to remain within the cylinder at maximum outreach to take up moments.

A very intuitive constraint is that the ROV must be able to pass through the hangar door without hitting the floor. This is checked by adding the two boxes to the left in Figure 4-1, representing the ROV and TMS dimensions, to the crane tip and making sure that it has enough clearance. If not, the calculations are aborted and another geometric setup is tested.

4.2.2 Cross sections

Each structural element is given a cross section and the cross sectional properties of the element are calculated. This gives the area moment of inertia, weight, and cross sectional area of each structural element.

Angles between the structural elements and the horizontal plane are needed in subsequent calculations of the forces and displacements. These angles are calculated in the geometry module and then passed on to the force and displacement calculations. All the necessary dimensions needed for calculation of the loads according to the classification societies are calculated in the geometry module and passed on to the load module.

4.2.3 Validation of geometric calculations

In order to validate the results from the geometry calculation module, two different methods have been used.

An animation showing the operation of the system is created in MATLAB to show that the motions of all nodes are as expected and that no irregularities occur when angles exceed critical values such as 90º and 180º. The animation runs from the minimum to the maximum value of both of the two primary angles, *alpha_A* and *alpha_B* in Figure 4-2, in the system and visualises all other nodal position as a function of these.

To validate the geometric model more in detail, a simple sketch in Autodesk Inventor is created. The sketch simply consists of line elements with the same local dimensions as the MATLAB model. By changing the two angles according to a testing scheme and measuring the global nodal positions in Inventor the correctness of the MATLAB model is validated with high accuracy.
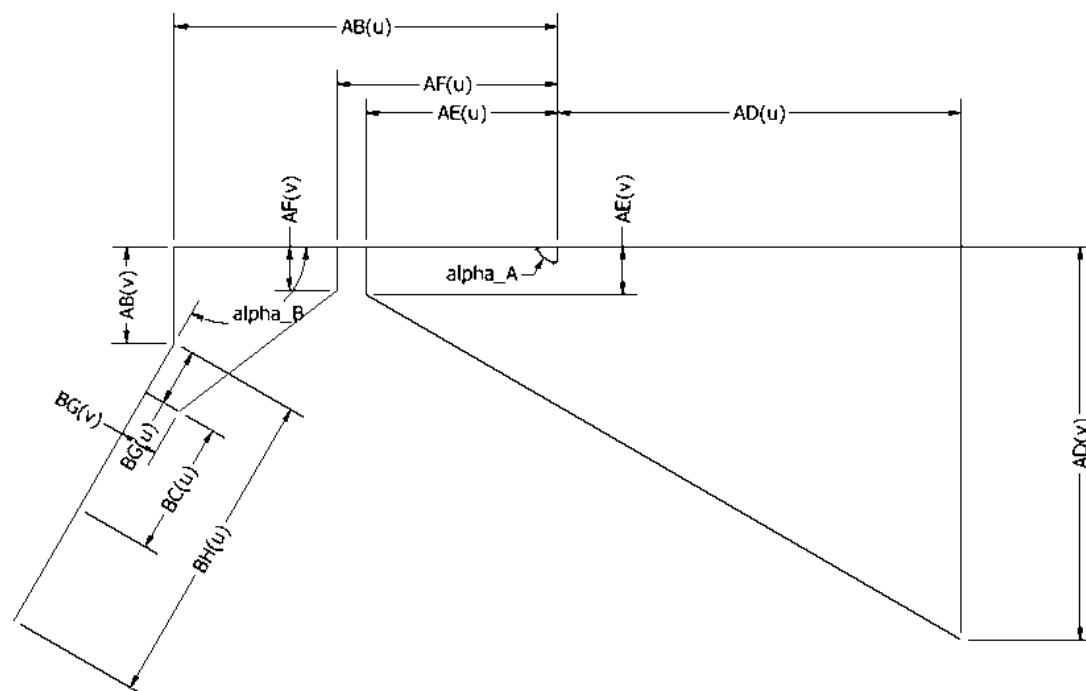

Figure 4-2 - Geometric validation model in Autodesk Inventor

4.3 Loads

To obtain the loads that need to be considered a MATLAB implementation of the class-rules from DNV and LR have been constructed. This is described in detail in Chapter 3.

4.3.1 Loads according to DNV

When calculating the dynamic loads according to DNV, the dynamic factor is used to translate a static load to a dynamic load. This dynamic factor is dependent on the stiffness of the entire system and the velocity of the crane tip relative to the load (see Section 3 for more details). The relative velocity in this case is the same as the relative velocity between the sea surface and the crane tip since the ROV is considered to follow the motions of the sea surface. The ROV moving through the splash zone is the most critical part of the operation from a structural point of view and this will cause the worst loading case.

The stiffness of the system depends on the geometric stiffness, i.e. the deflection of the structure due to a unit load. To calculate this deflection the stiffness of the hydraulic system, umbilical cable, and the steel structure need to be known. Umbilical stiffness varies depending on the type of cable and manufacturer, but a value for this is assumed based on data from manufacturers. Stiffness of the hydraulic system is not covered in this project but some standard values can also be assumed. Stiffness of the steel structure is calculated in the strength module and this will depend on the added load.

Since the stresses and not the deflections are the dimensioning parameters, the structure must be designed to minimize the stresses and maximize the deflection. This reduces the dynamic factor and hence makes the critical load smaller. This process is iterated since after each design loop, the assumed deflection that is used to calculate the load has to be compared to the deflection calculated for the actual structure. This could possibly result in larger deflection than the assumed while the stresses are manageable, meaning that the dynamic factor can be decreased to match the new deflection.

In the next design loop the load is smaller and therefore the stresses are lower. The structure is then optimized for this load and the deflection is checked again and compared to the previous value. Using DNV's rules gives more freedom to iterate and optimize the structure further compared to LR's, however the optimized load according to DNV may not be smaller than the load given by LR.

For this project a fixed dynamic factor of three is used for calculations of the load according to DNV, see Section 3.1.2 for more details. Because of this assumption there is no need to assume any values for umbilical stiffness or hydraulic stiffness at this point. The assumption of a dynamic factor of three is to make the structure more generally applicable to different vessels.

4.3.2 Loads according to Lloyd's Register

Load calculations according to LR are more prescriptive than for DNV and are described in more detail in Section 3.2.

4.4 Strength

For the strength calculations two different methods are used. The reason for using two models to calculate the same thing is that the first model does not produce reliable results when validating the stresses. Therefore another attempt with a much simpler model is performed.

4.4.1 Strength Model One

The approach first chosen for strength calculation is based on the finite element method. A two dimensional representation of the structure with three degrees of freedom in each node is used to calculate nodal displacements due to external loads in one or several nodes. The model uses a matrix formulation to superposition the stiffness contribution in all three degrees of freedom in each node to form the total stiffness in each node and the whole system. The idea is to combine a bar element that can take axial load with a beam element that can take lateral load and nodal rotation to get a frame element that can resist loading in all three directions (axial, lateral and nodal rotation). The stiffness in each node is found by super positioning of the stiffness of all of the connecting elements. The nodal stiffness is defined in global coordinates and the element contributions are found by transforming the element stiffness from local to global coordinates. This transformation is performed with a transformation matrix that contains the angle between the horizontal plane and the element. When the total global stiffness of each node is known, the external forces are added and global nodal displacements are calculated. These are transformed back to local coordinates for each element to calculate the forces and moments acting on the element. Stresses are easily obtained by considering the calculated forces and moments in combination with the cross sectional data (Liu & Quek. 2013).

Benefits of this approach are that it can easily be iterated for different geometric input, every element is assigned specific mechanical properties and it is possible to expand the model to cover all degrees of freedom. The calculation process is automatized to a large extent, making it possible to increase the number of elements in the model. This makes it possible to increase the accuracy of the results further on. This model is valid for all positions of the crane and if a specific position is of interest, the results for this position are obtained easily.

The calculation procedure for this model is divided into four steps followed by validation and optimization.
1. Domain discretization and application of loads
2. Boundary conditions
3. Element forces
4. Stress calculations

To begin with the structure is divided into a minimum number of elements and nodes to make it easy to handle and verify.
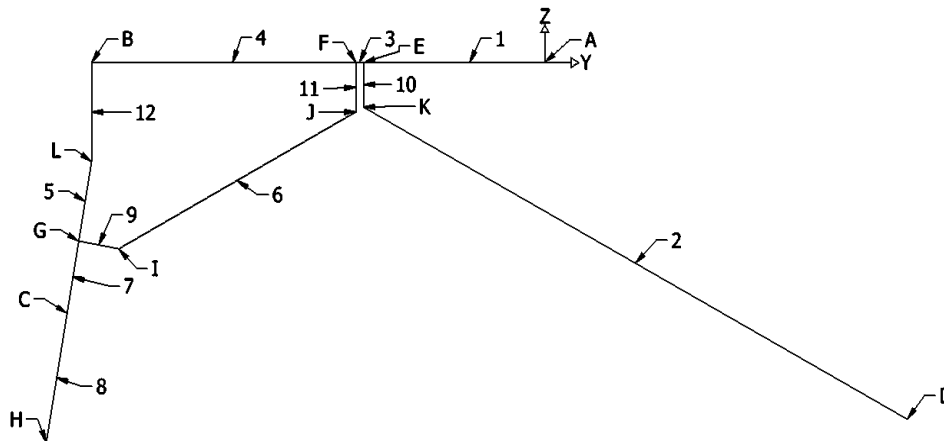
Figure 4-3 - Definition of elements and nodes used for strength calculations

With the data calculated in the geometry- and load-module, the displacements and rotations in each node are calculated. Each node (A to L in Figure 4-3) is displaced in the horizontal and vertical direction as well as rotate. The own weight of each element are added as nodal forces and moments and the load is applied in node H, see Figure 4-3. The load will act both vertically and horizontally since the umbilical cable runs over a sheave and result in both horizontal and vertical components.

To be able to solve the system of equations to obtain the displacements, some boundary conditions needed to be introduced to prevent rigid body motions. Node A and node D in Figure 4-3 are both fixed in radial and axial direction but free to rotate. This represents ideal hinges with no friction which is a reasonable approximation for this structure. The calculated displacements are used to calculate the forces acting in each node of the structure and then these forces are transformed to the local element coordinate system to prepare for stress calculations.

Normal stresses in each element are calculated from the axial element forces and bending moments acting on each element. Stresses due to bending are compressive on one side of the element and tensile on the other side. Depending on if the axial load is compressive or tensile, the critical normal stress will occur in the upper or lower fibre of the element. The relation between normal stress, axial load and bending is shown in equation 4.1 (Lundh, 2000).

$$\sigma_N = \frac{N}{A} + \frac{M}{I} z \qquad\qquad \text{Eq. 4.1}$$

To validate the calculated displacements, a testing function is constructed in MATLAB. The function applies a load with a fixed magnitude and rotates the direction 360° and saves the displacement in each node for each direction. The purpose is to make sure no irregularities occur for any direction of the load. Horizontal and vertical displacements as well as the rotation of each node are plotted against the force direction and then checked so that they create smooth curves without singularities or other unwanted effects. The results are displayed in Figure 4-4 to 4-6 and as can be seen, the displacements behave as anticipated. In Figure 4-4b, 4-5b and 4-6b, some of the displacements become negative and therefore make an extra loop in the plot. The negative displacements are only indicating the direction of the displacement and are not to be interpreted as errors in the model. Since the direction of the load is rotated while the direction of the own weight is fixed, it is reasonable that some of the displacements change direction somewhere during the cycle. In Figure 4-4a, 4-5a and 4-6a, the displacements are symmetric since there is no own

weight offsetting the direction of the displacements. As can be seen in the legend box in the Figure 4-4 to 4-6, the curves of the nodes closest to the load (node G, C and B, see Figure 4-3) are scaled down. The displacements in these nodes are significantly larger since they are located far away from the fixed nodes (node A and D, see Figure 4-3). This is to make it possible to plot all curves together
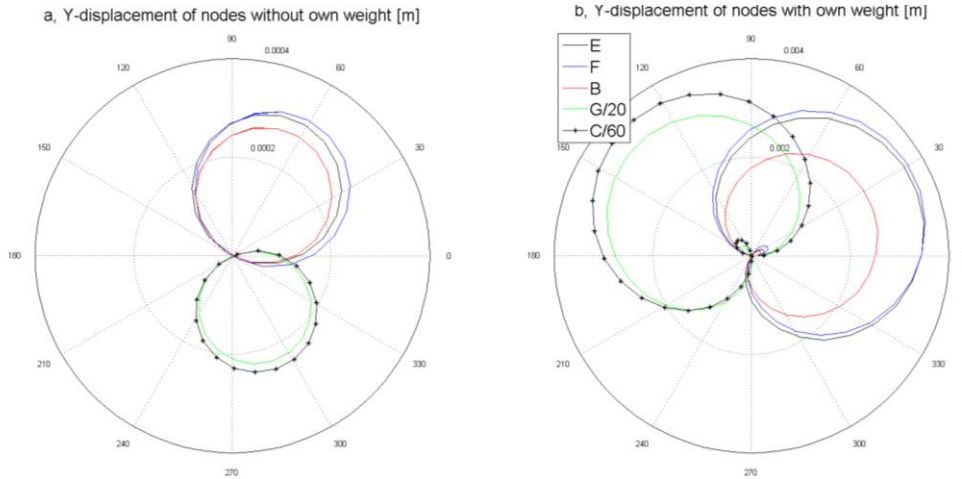
Figure 4-4 - Horizontal displacement for different load directions
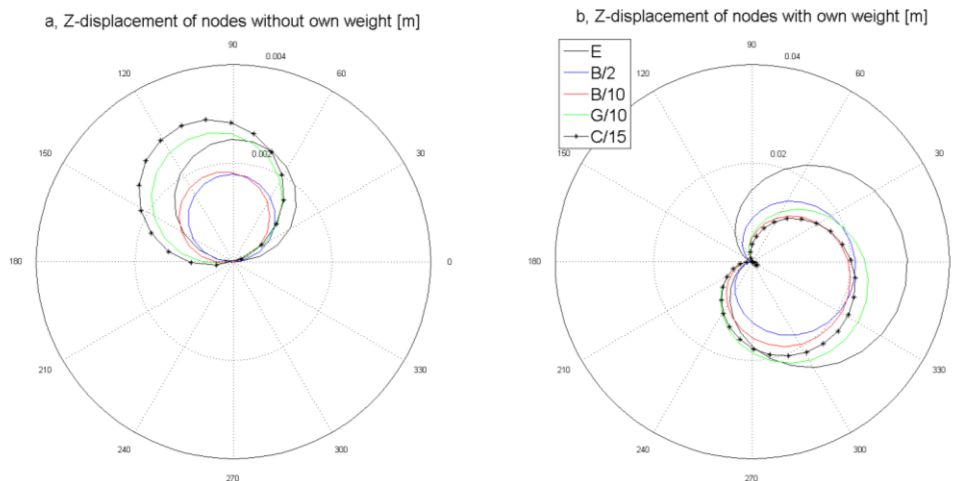
Figure 4-5 - Vertical displacement for different load directions
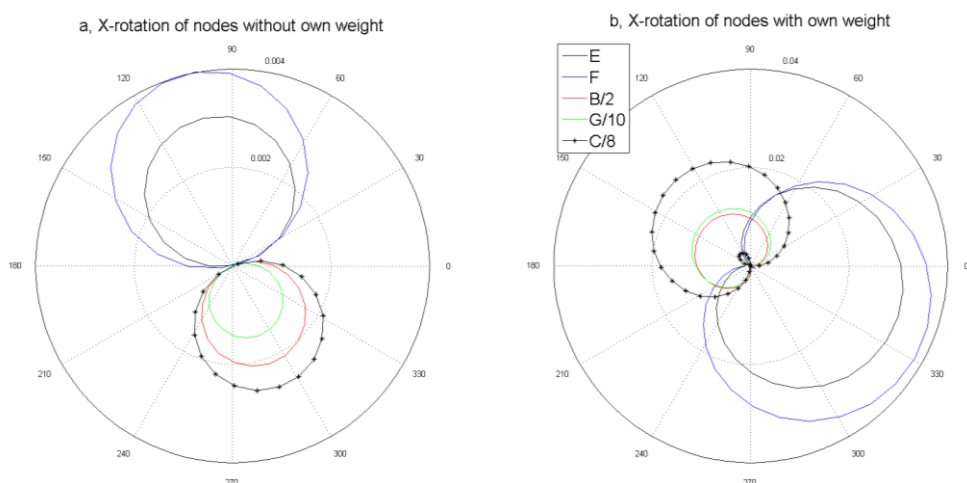
Figure 4-6 - Nodal rotation for different load directions

Since there is a visualisation of the geometry available from the geometry module, this is also used with the displacement data added to show the magnitude and direction of the nodal displacements. This is a very useful tool to get an instant overview of how changes in load or geometry affect the nodal displacements of the structure. It also makes it possible to determine if the displacements are reasonable.

When the stresses are verified, it is found that they behave in an unrealistic way. When the outreach of the crane is increased, some stresses increase as expected while others decrease. Also, the stresses in the element closest to the wall (element 1, see Figure 4-3) became too small and the reaction forces in the door hinge (node A, see Figure 4-3) are far smaller than they should be. Stresses in the two elements closest to the load (element 7 and 8, see Figure 4-3) are as anticipated and are verified by simple hand calculations. In the node where the hydraulic cylinder between the side door and the A-frame is attached (node G, see Figure 4-3), the stresses are distributed incorrectly and give the unrealistic behaviour. This error is then transferred throughout the structure and in every node where three elements are attached (node G, F and E, see Figure 4-3) the stresses are distributed incorrectly. In Section 6.1, Comparison of strength models, the forces and moments in all nodes are compared between strength model one and two and this comparison gives a good overview of where the calculations go wrong. In order to verify the results from this model, the second strength model is used.

4.4.2 Strength model two

As a second attempt, a simpler model is constructed to get reliable results. This model uses beam theory and starts with free body diagrams of the structure and expressions for the moment and forces in all of the nodes are derived as functions of the applied load and the geometry.

The most critical case is when the crane is hoisting the ROV through the splash zone at maximum outreach since this will maximize the bending moment in the structure. Hence, this is the primary case of interest. One drawback of this model compared with model one is that a separate free body diagram is needed for all of the operational modes. On the other hand the critical operational modes are easily identified.

Cylinder forces are found by formulating moment equilibrium around node A and node B (see Figure 4-3) and solving for the relevant forces. The maximum pulling force for the cylinder attached to the A-frame (element 6, see Figure 4-3) is calculated from a separate free body diagram. This free body diagram describes the condition when the door is full closed and the angle between the A-frame and the door (α_B see Figure 4-2) is 90°. This gives the worst loading case for the pulling force of this cylinder.

Stresses are calculated in the same way as in strength model one; by adding the axial force contribution to the bending moment contribution to the normal stress in each beam.

Since this model only uses two different operating conditions, i.e. at maximum outreach and maximum in-reach, there is not the same need for a systematic validation of the forces and stresses. Instead this has been done by hand by simply calculating all of the moments used for the stress calculations and checking that the results are reasonable and that the forces and moments behave as they should. This is one of the benefits with this model; it is much easier to get an overview of.

4.5 Strength constraints

Excessive yielding is checked by comparing the calculated stresses with the highest permissible stresses for the material and the critical load case. According to DNV this will be load case two and the permissible stress is the yield strength of the material divided by 1.33. Material selection is described more in detail in Section 3.1.1 and the lowest available yield stress is 235 MPa, which give a permissible stress of 176 MPa. To reduce the weight of the structure, steel of higher yield strengths are used where it is found necessary.

The hydraulic cylinders are loaded in compression in the worst loading case; hence they need to be checked with respect to buckling. Other parts of the structure are not significantly loaded in compression; hence these are not subjected to buckling.

4.6 Hydraulic cylinders

The hydraulic cylinders are chosen from the TTS Ships Equipment standard library and the dimensioning process considers cylinder buckling, pushing and pulling force and length requirements.

To choose appropriate cylinders, the first step is to calculate the needed pushing force. This is done together with the other force calculations and then used to calculate a minimum piston diameter. The closest larger piston diameter is then found in the hydraulic cylinder library and this cylinder is tested with respect to the criteria's. If the cylinder fails at any of the criteria's, the next larger one is chosen instead and the calculations are iterated until a suitable one is found.

For the cylinder between the hangar wall and the door, the hangar wall attachment coordinates need to be defined. This is done by first calculating the pushing force needed at a fixed angle between the cylinder and the door, and then a cylinder matching this requirement is chosen. The minimum length of the cylinder is calculated and the coordinates are then found by moving in the direction of the cylinder in small steps until the cylinder fits. The objective is to keep the cylinder as far away from the working environment as possible, i.e. as far up from the hangar floor and as close to the hangar door as possible.

The positioning of the cylinder attachments between the A-frame and the door are more restricted. This cylinder needs to provide the needed force while being small enough in the folded condition. Cylinder attachment positions are found by testing a lot of combinations and then these combinations have been normalized by length of the door and outreach. Pulling force of this cylinder is of interest since it must be able to lift the ROV inside the hangar and this criterion is simply checked in the end of the calculations. If it does not fulfil the requirement a larger cylinder is chosen and the calculations are iterated.

Buckling calculations are performed according to DNV (1999) and a minimum buckling safety factor of 2.3 is used.

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5   Results

The result of this project is a concept for an overhead LARS and a calculation tool that is used to design the system for various vessels. In the following sections the results are presented more thoroughly.

5.1   Calculation tool

To show the versatility of the tool, the output from four different cases is compared in this section. The primary variable of the cases is the outreach, which varies between 3 300 – 6 600 mm, while all other components are dimensioned relative to the chosen outreach. The four cases tabulated in Table 5-1 are dimensioned according to the regulations of both LR and DNV. As can be seen in the table, there are only minor differences between the two.

Table 5-1 Output data, LR and DNV

	Case 1 LR/**DNV**	Case 2 LR/**DNV**	Case 3 LR/**DNV**	Case 4 LR/**DNV**
Outreach [mm]	3 300/**3 300**	4 400/**4 400**	5 500/**5 500**	6 600/**6 600**
SWL [kg]	5 000/**5 000**	15 000/**15 000**	15 000/**15 000**	15 000/**15 000**
Upper Door Length [mm]	3 000/**3 000**	4 000/**4 000**	5 000/**5 000**	6 000/**6 000**
Lower Door Length [mm]	7 000/**7 000**	6 000/**6 000**	5 000/**5 000**	4 000/**4 000**
In-reach [mm]	2728/**2728**	3303/**3303**	3879/**3879**	4 455/**4455**
Duty Factor	1.2/ **N/A**	1.2/ **N/A**	1.2/ **N/A**	1.2/ **N/A**
Dynamic factor	N/A /**3**	N/A /**3**	N/A /**3**	N/A/**3**
Hoisting Factor	2.5 /**N/A**	2.5 /**N/A**	2.5 /**N/A**	2.5 /**N/A**
Significant Wave height [m]	5/**5**	5/**5**	5/**5**	5/**5**
Calculated Load [kg]	21 442/ **20 870**	64 313 /**62600**	64 316 /**62603**	64 319 /**62605**
Maximum allowable height of ROV + TMS [mm]	7 101*/**7 101***	6 338*/**6 338***	5 552*/**5 552***	4 754*/**4 754***
Steel Weight [kg]	7 765/**7 659**	17 865/**17 502**	23 263/**22 688**	29 105/**28 352**
Diameter Cylinder 1/2 mm]	220/220 / **220/220**	380/360 / **380/350**	400/350 / **400/340**	400/340 / **400/340**
Position of cylinder wall attachment [mm]	y: 2 390 z: -2 749 **y: 2 390** **z: -2 749**	y: 3 356 z: -3 605 **y: 3 356** **z: -3 605**	y: 3 898 z: -4 196 **y: 3 898** **z: -4 196**	y: 4 432 z: -4 781 **y: 4 432** **z: -4 781**

*Assuming a hangar opening height of 10 000 [mm]

In all cases, the hangar opening height is set to 10 000 mm, which represents the height of the reference vessels hangar. This combination with e.g. the shortest crane is not a good solution since the ROV will have to be hoisted down to the deck inside the hangar. However, this is done in order to keep the comparison reasonably small and graspable.

In the beginning of the project, some ROV and TMS dimensions are approximated from data sheets of existing products that should be possible to use with this LARS. These values are not presented in the comparison; instead the maximum allowable height of the suspended load is presented. This makes the comparison easier, but the possibility to check the clearance for a specific ROV and TMS still remains and these parameters can easily be changed in the input sheet.

Total outreach is set as 110 % of the length of the hangar door and this sets the dimensions of the A-frame. This is a small increase in the outreach in relation to how many extra components that are added, but the increased outreach is not the primary function of the A-frame. The large benefit of the A-frame is the possibility of reaching far into the hangar and placing the ROV and the TMS on the hangar floor independently. This is where the telescopic part of the crane adds extra value to the design, justifying the extra complexity of the design.

Case 1 with the shortest outreach has an SWL of only 5 000 kg while all of the other cases are calculated with an SWL of 15 000 kg. This is due to geometric constraints which makes it difficult to fit a strong enough cylinder between the door and the A-frame when the outreach is as short as in this case. The positions of cylinder hinges are normalized as fractions of the length of the door and these relations are the same for the entire range of outreaches. This is to make the product easily scalable, but the drawback is that the relations are optimized for an outreach of 5500 mm so any other outreach is slightly sub optimized.

The smallest crane is best suited for hangars that are located closer to the sea surface, due to the risk of the ROV hitting the side of the vessel during the lowering operation.

For case 2-4 the SWL is 15 000 kg and the outreach is increased from 4 400 – 6 600 mm. The calculated load according to the class rules increases only slightly with the increased outreach, but since the outreach increases the moment arm of the load is increased. The applied load can of course be decreased, resulting in decreased material thickness and cylinder dimensions, creating a lighter structure.

An interesting phenomenon is that the diameter of the cylinder between the side door and the A-frame decreases as the outreach is increased, which could seem counter intuitive. This is due to the fact that the length of the side door increases more than the length of the A-frame when the total outreach is increased, hence the moment around the hinge between the side door and the A-frame does not increase very much. Meanwhile, the position of the cylinder hinge on the side door is moved to a more beneficial position, making the needed cylinder force smaller.

The position of the wall attachment for the side door cylinder is calculated in an iteratively way and with a fixed angle between the side door and the hydraulic cylinder. This makes the needed force to keep the door open constant and the only variable is the length of the cylinder. The location is a trade-off between keeping the hydraulic cylinder as far away from the working environment on the deck as possible while the cylinder size is reasonably small.

For each case, the total steel weight is calculated and presented in the output file. This weight is to be seen as a rough approximation since the side door is only approximated as a simple beam with a hollow rectangular cross section. When the detailed design of the side door is performed a more accurate weight is obtained.

Calculations have been performed in a two dimensional case and loads due to torsion have not been considered. To account for some of this, an uneven load distribution has been assumed and each side of the structure is loaded with 70% of the total load instead of 50 % which would represent totally even load distribution.

The telescopic joint has not been designed in detail and the loads in this section should preferably be subjected to a FEM analysis. Most probably the shear stresses in this section are significant and demand some special consideration.

5.2 Visualization

This section provides figures from the CAD-modelling to give a visualization of the developed launch and recovery system. In Figure 5-1 a side view of the crane, inside the hangar, with the attached ROV can be seen. This is a launching sequence where the ROV has just been lifted from the hangar floor, and is being directed over board for the lowering operation.
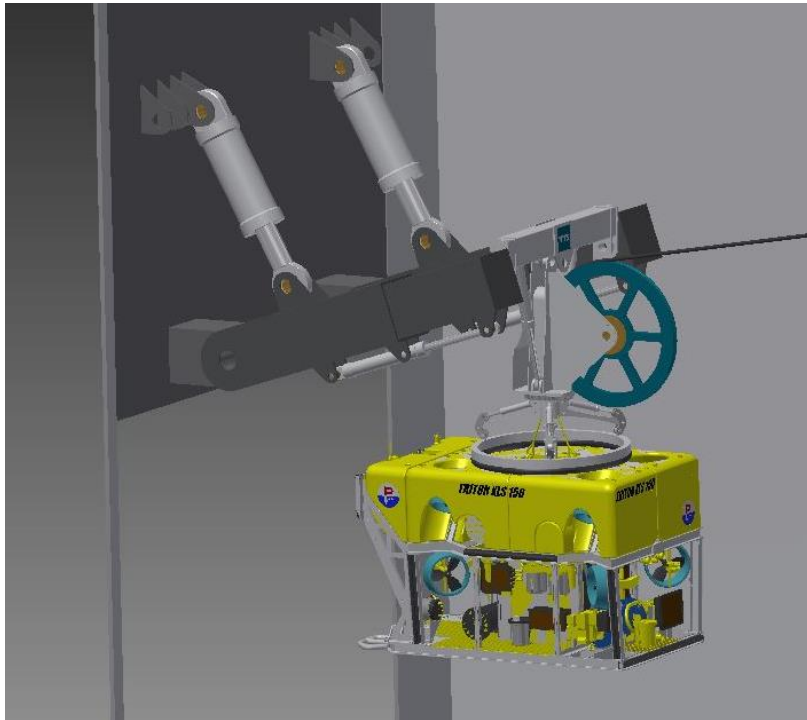

Figure 5-1 Side view of the LARS in a stowed position

In Figure 5-2 a rear view of the LARS is seen, again with the attached ROV and inside the hangar. The empty cylinder ears in the middle of the figure hold the cylinders opening the door. These cylinders are left out from the figures to give a clear view of the system.

Figure 5-2 Rear view of the LARS in a stowed position

6 Discussion

An overhead launch and recovery system and a design tool that offers the possibility to adapt the design to various vessels are developed in this project. The largest challenge during the project is to develop a concept that is simple and flexible while still offering the functionality needed for the operations.

One of the primary demands on the concept is that it shall be possible to integrate with other products from TTS Ships Equipment to complete their product range of hangar equipment. This demand is fulfilled and when this concept is ready to be introduced to the market it will be sold in a package with hangar doors designed at TTS Ships Equipment.

Since the concept is directed towards offshore supply vessels, the flexibility is of high importance. Offshore supply vessels are not built in large series and are often one-off designs. To dimension equipment that suits all vessels in this category is impossible; instead focus is to keep as many parameters as possible open. This makes it possible to design systems that can be successfully fitted into a large number of ROV hangars. The design tool makes this possible and at its current stage, it can very easily be used to dimension systems with an SWL of up to 15 tonnes and an outreach of up to 6.6 m. With only a very limited number of input parameters, the most essential details can be calculated. This has been one of the goals for this project and it has been fulfilled.

The design tool still allows a large number of parameters to be changed to match very specific requirements from the customer, but often only a minimum amount of input data is available. Hence, approximations and assumption in the calculation tool creates a concept to start off from.

When a LARS is to be designed for a given vessel, this calculation tool can very early in the process give a good estimation of how the system will look in the end. This information can be used to get an idea of how the interface between the LARS and the vessel needs to be designed and where extra reinforcements are needed. This together with the approximate steel weight and the cylinder dimensions can give rough cost estimation for the system.

The proposed design is very small in its stowed condition and it does not occupy any of the hangar deck space, which is highly appreciated by the operators since there is always a lack of space onboard. Cylinder attachments are placed high above the deck level to be out of the way for other activities in the hangar.

Performing a weighted evaluation matrix with very little experience is difficult and the results might not be accurate. Therefore it is very important to get input from engineers experienced in the field. After the discussions regarding the concepts it was established that the weights were inaccurate and that other aspects should be taken into consideration. Therefore, the generated concepts were put aside and new concepts developed, now with help from experts.

6.1 Comparison of strength models

Since model one does not provide reliable results, a comparison of the two models is performed. In each node, the forces and moments are compared to find the error in model one. The comparison starts at the node where the load is applied and then moves towards the vessel and ends up in the hinge between the vessel and the side door.

As can be seen in Figure 6-1, the forces are equal in the first two nodes but the directions are opposite in node H. Also, there is a small bending moment acting in node H which should not be there. In node C the results are the same from both models, but in node G the problems begin. The problem is that the forces and moments do not distribute in a correct way in nodes where three elements are connected. It can also be assumed that the error in node G transfers throughout the structure. As can be seen in Figure 6-1, the results are totally different between the two models in all other nodes than node H and C.
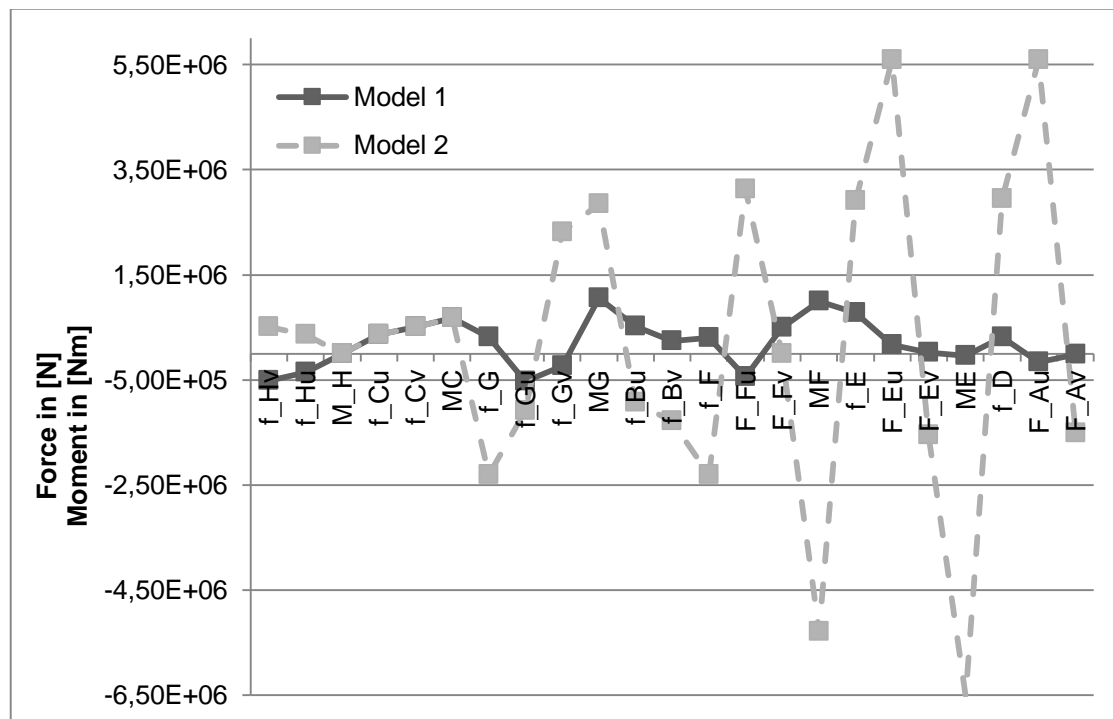

Figure 6-1 - Comparison of strength models

The source of the problem has not been found even though several extensive attempts have been made.

7 Conclusion

The thesis presents a concept for an overhead launch and recovery system and a design tool that offers the possibilities to adapt the design to various vessels. The concept is simple and flexible while still offering the functionality needed for the operations. One of the primary demands on the concept is that it should be possible to integrate with other TTS Ships Equipment products, in order to complete their product range of hangar equipment. This demand has been fulfilled and when this concept is ready to be introduced to the market it can be sold in a package with hangar doors designed and other hangar equipment designed at TTS Ships Equipment.

When developing a product intended for small production series the adaptability is crucial for the success of the product. The possibility to reproduce the calculations with minor changes is important in order to reduce design cost and improve the economic margins. The design tool allows for simple reproducibility of the calculations, making it very quick and easy to change most of the parameters. This is a very useful tool since it provides the main dimensions of the system very early in the design process. To have the main dimensions early will reduce the number of design iterations needed to get a system that fits the considered vessel and fulfills the classification society's rules.

A product that is possible to integrate with other products from TTS Ships Equipment give a large benefit since a more complete solution can be sold to the customer. The customer do not need to consider the interface between equipment from different manufacturers, instead everything is delivered as a package that is already optimized to work together. Since the existing TTS products cover most other hangar equipment, the LARS completes the product range in a very good way.

Regarding the calculations, the major conclusion is that a simple model that can be is always preferable over a more complicated model that is more exact but harder to verify. A calculation model that is as simple as possible should always be the goal, since even a very simple model become very complex in the end. This complexity of even simple concepts and calculation models derives from the huge amount of demands from customers, classification societies and manufacturers. The developed concept and calculation model does consider a large amount of demands from the different stakeholders. This is possible due to the systematic concept development approaches that is used throughout the project and ensure that the end product fulfills all of the identified demands.

This thesis has taken the first steps in the developing process of an overhead launch and recovery system. A lot of work remains but this thesis provides a foundation to build from. The developed concept is good and provides a large customer value while filling an important gap in the product range of TTS Ships Equipment. However, it requires more detailed design work and more verification before it is ready to be introduced to the market.

8 Future work

A FEM simulation tool can be used to validate the calculations done in MATLAB. This is an accurate way of seeing if the dimensions calculated are strong enough and where they have to be improved. Also some critical points in the structure should be investigated in a detailed FEM-analysis to ensure the structural integrity of the design.

Limiting the number of classification societies used during the calculations to DNV and LR is based on the customer preferences and standards at TTS Ships Equipment. In order to get a more thorough evaluation of the calculations, the rules of other class societies can be implemented in the MATLAB code. This is useful if the customer prefers another society than the two that have been used.

The solution of the overhead LARS includes the hangar doors. These are existing solutions at TTS which have to be modified. As the project progresses in the future, the door on which the LARS is attached will have a more detailed structure than shown in the CAD pictures and used in the calculations.

The door that the LARS is integrated with does not cover the whole opening, requiring additional doors to close the hangar opening. There are different solutions for these doors, which will ensure weather protection during the ROV operation, but this is left for future work.

As the calculations are now, the structure is considered to be two dimensional and the effects of torsion to the structure are only considered by loading the structure unevenly. This means that there is no shear stress due to torsion included in the model which needs to be investigated more in detail.

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Appendix A – Output data

Outreach = 3300 mm, DNV

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: DNV
Strength Model: 2

SWL = 5000 [kg]
Calculated Load = 20870 [kg]
Upper Door Length = 3500 [mm]
Lower Door Length = 6500 [mm]
Hangar Height = 10000 [mm]
Outreach = 3300 [mm]
In reach = 2728 [mm]
Steel Weight = 7654 [kg]

Cylinder 1 Dimensions:
Index = 27 øD = 220.0   ød = 140.0 øB = 273.0 A = 645.0 J/F = 150.0   H = 180.0 øG = 110.0 H_MIN = 160.0

Cylinder 2 Dimensions:
Index = 27 øD = 220.0   ød = 140.0 øB = 273.0 A = 645.0 J/F = 150.0   H = 180.0 øG = 110.0 H_MIN = 160.0

Minimum Clearance = 1656 [mm] OK
Maximum allowable height of ROV + TMS = 7101 [mm]

Position of cylinder wall attachment:
 y-coordinate = 2390 [mm]
 z-coordinate = -2749 [mm]

Reaction force at hangar wall = 825.66 [kN]

Diameter of hinge pin A = 107.76 [mm]
Diameter of hinge pin D = 94.18 [mm]

Stresses:
 Element 1 = 258.82 [MPa]
 Element 2 = Cylinder
 Element 3 = 258.82 [MPa]
 Element 4 = 265.28 [MPa]
 Element 5 = 184.68 [MPa]
 Element 6 = Cylinder
 Element 7 = 24.41 [MPa]
 Element 8 = 162.50 [MPa]

Outreach = 4400 mm, DNV

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: DNV
Strength Model: 2

SWL =   15000 [kg]
Calculated Load = 62600 [kg]
Upper Door Length =   4500 [mm]
Lower Door Length =   5500 [mm]
Hangar Height = 10000 [mm]
Outreach = 4400 [mm]
In reach =   3303 [mm]
Steel Weight = 17275 [kg]

Cylinder 1 Dimensions:
Index = 52 øD = 380.0   ød = 300.0 øB = 495.0 A = 1125.0 J/F = 265.0   H = 300.0 øG = 200.0 H_MIN = 280.0

Cylinder 2 Dimensions:
Index = 45 øD = 350.0   ød = 250.0 øB = 435.0 A = 1075.0 J/F = 250.0   H = 265.0 øG = 180.0 H_MIN = 245.0

Minimum Clearance = 893 [mm] OK
Maximum allowable height of ROV + TMS = 6338 [mm]

Position of cylinder wall attachment:
 y-coordinate = 3356 [mm]
 z-coordinate = -3605 [mm]

Reaction force at hangar wall = 2698.00 [kN]

Diameter of hinge pin A = 186.59 [mm]
Diameter of hinge pin D = 155.78 [mm]

Stresses:
 Element 1 = 266.15 [MPa]
 Element 2 = Cylinder
 Element 3 = 266.15 [MPa]
 Element 4 = 264.16 [MPa]
 Element 5 = 222.63 [MPa]
 Element 6 = Cylinder
 Element 7 = 86.46 [MPa]
 Element 8 = 264.40 [MPa]

Outreach = 5500 mm, DNV

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: DNV
Strength Model: 2

SWL =   15000 [kg]
Calculated Load = 62602 [kg]
Upper Door Length =   5500 [mm]
Lower Door Length =   4500 [mm]
Hangar Height = 10000 [mm]
Outreach = 5500 [mm]
In reach =   3879 [mm]
Steel Weight = 22379 [kg]

Cylinder 1 Dimensions:
Index = 52 øD = 380.0   ød = 300.0 øB = 495.0 A = 1125.0 J/F = 265.0   H = 300.0 øG = 200.0 H_MIN = 280.0

Cylinder 2 Dimensions:
Index = 42 øD = 340.0   ød = 220.0 øB = 419.0 A = 1075.0 J/F = 250.0   H = 260.0 øG = 180.0 H_MIN = 245.0

Minimum Clearance = 107 [mm] OK
Maximum allowable height of ROV + TMS = 5552 [mm]

Position of cylinder wall attachment:
 y-coordinate = 3898 [mm]
 z-coordinate = -4196 [mm]

Reaction force at hangar wall = 2853.87 [kN]

Diameter of hinge pin A = 189.32 [mm]
Diameter of hinge pin D = 160.22 [mm]

Stresses:
 Element 1 = 266.74 [MPa]
 Element 2 = Cylinder
 Element 3 = 266.74 [MPa]
 Element 4 = 265.61 [MPa]
 Element 5 = 230.96 [MPa]
 Element 6 = Cylinder
 Element 7 = 139.16 [MPa]
 Element 8 = 234.24 [MPa]

Outreach = 6600 mm, DNV

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: DNV
Strength Model: 2

SWL =   15000 [kg]
Calculated Load = 62605 [kg]
Upper Door Length =   6500 [mm]
Lower Door Length =   3500 [mm]
Hangar Height = 10000 [mm]
Outreach = 6600 [mm]
In reach =   4455 [mm]
Steel Weight = 27928 [kg]

Cylinder 1 Dimensions:
Index = 55 øD = 400.0   ød = 340.0 øB = 508.0 A = 1125.0 J/F = 265.0   H = 320.0 øG = 200.0 H_MIN = 280.0

Cylinder 2 Dimensions:
Index = 42 øD = 340.0   ød = 220.0 øB = 419.0 A = 1075.0 J/F = 250.0   H = 260.0 øG = 180.0 H_MIN = 245.0

Minimum Clearance = -691 [mm] OK
Maximum allowable height of ROV + TMS = 4754 [mm]

Position of cylinder wall attachment:
 y-coordinate = 4432 [mm]
 z-coordinate = -4781 [mm]

Reaction force at hangar wall = 2990.88 [kN]

Diameter of hinge pin A = 191.47 [mm]
Diameter of hinge pin D = 164.02 [mm]

Stresses:
 Element 1 = 266.41 [MPa]
 Element 2 = Cylinder
 Element 3 = 266.41 [MPa]
 Element 4 = 264.83 [MPa]
 Element 5 = 236.92 [MPa]
 Element 6 = Cylinder
 Element 7 = 164.89 [MPa]
 Element 8 = 245.69 [MPa]

Outreach = 3300 mm, Lloyds Register

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: Lloyds
Strength Model: 2

SWL =   5000 [kg]
Calculated Load = 21442 [kg]
Upper Door Length =   3500 [mm]
Lower Door Length =   6500 [mm]
Hangar Height = 10000 [mm]
Outreach = 3300 [mm]
In reach =   2728 [mm]
Steel Weight = 7760 [kg]

Cylinder 1 Dimensions:
Index = 27 øD = 220.0   ød = 140.0 øB = 273.0 A = 645.0 J/F = 150.0   H = 180.0 øG = 110.0 H_MIN = 160.0

Cylinder 2 Dimensions:
Index = 27 øD = 220.0   ød = 140.0 øB = 273.0 A = 645.0 J/F = 150.0   H = 180.0 øG = 110.0 H_MIN = 160.0

Minimum Clearance = 1656 [mm] OK
Maximum allowable height of ROV + TMS = 7101 [mm]

Position of cylinder wall attachment:
 y-coordinate = 2390 [mm]
 z-coordinate = -2749 [mm]

Reaction force at hangar wall = 848.38 [kN]

Diameter of hinge pin A = 108.83 [mm]
Diameter of hinge pin D = 95.12 [mm]

Stresses:
 Element 1 = 254.41 [MPa]
 Element 2 = Cylinder
 Element 3 = 254.41 [MPa]
 Element 4 = 256.69 [MPa]
 Element 5 = 189.73 [MPa]
 Element 6 = Cylinder
 Element 7 = 25.08 [MPa]
 Element 8 = 166.95 [MPa]

Outreach = 4400 mm, Lloyds Register

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: Lloyds
Strength Model: 2

SWL =   15000 [kg]
Calculated Load = 64312 [kg]
Upper Door Length =   4500 [mm]
Lower Door Length =   5500 [mm]
Hangar Height = 10000 [mm]
Outreach = 4400 [mm]
In reach =   3303 [mm]
Steel Weight = 17661 [kg]

Cylinder 1 Dimensions:
Index = 52 øD = 380.0   ød = 300.0 øB = 495.0 A = 1125.0 J/F = 265.0   H = 300.0 øG = 200.0 H_MIN = 280.0

Cylinder 2 Dimensions:
Index = 48 øD = 360.0   ød = 220.0 øB = 445.0 A = 1075.0 J/F = 250.0   H = 280.0 øG = 180.0 H_MIN = 245.0

Minimum Clearance = 893 [mm] OK
Maximum allowable height of ROV + TMS = 6338 [mm]

Position of cylinder wall attachment:
 y-coordinate = 3356 [mm]
 z-coordinate = -3605 [mm]

Reaction force at hangar wall = 2767.86 [kN]

Diameter of hinge pin A = 189.32 [mm]
Diameter of hinge pin D = 157.98 [mm]

Stresses:
 Element 1 = 265.47 [MPa]
 Element 2 = Cylinder
 Element 3 = 265.47 [MPa]
 Element 4 = 264.72 [MPa]
 Element 5 = 221.11 [MPa]
 Element 6 = Cylinder
 Element 7 = 88.83 [MPa]
 Element 8 = 227.46 [MPa]

Outreach = 5500 mm, Lloyds Register

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: Lloyds
Strength Model: 2

SWL =   15000 [kg]
Calculated Load = 64315 [kg]
Upper Door Length =   5500 [mm]
Lower Door Length =   4500 [mm]
Hangar Height = 10000 [mm]
Outreach = 5500 [mm]
In reach =   3879 [mm]
Steel Weight = 22972 [kg]

Cylinder 1 Dimensions:
Index = 55 øD = 400.0   ød = 340.0 øB = 508.0 A = 1125.0 J/F = 265.0   H = 320.0 øG = 200.0 H_MIN = 280.0

Cylinder 2 Dimensions:
Index = 45 øD = 350.0   ød = 250.0 øB = 435.0 A = 1075.0 J/F = 250.0   H = 265.0 øG = 180.0 H_MIN = 245.0

Minimum Clearance = 107 [mm] OK
Maximum allowable height of ROV + TMS = 5552 [mm]

Position of cylinder wall attachment:
 y-coordinate = 3898 [mm]
 z-coordinate = -4196 [mm]

Reaction force at hangar wall = 2941.25 [kN]

Diameter of hinge pin A = 192.22 [mm]
Diameter of hinge pin D = 162.86 [mm]

Stresses:
 Element 1 = 265.46 [MPa]
 Element 2 = Cylinder
 Element 3 = 265.46 [MPa]
 Element 4 = 263.62 [MPa]
 Element 5 = 230.02 [MPa]
 Element 6 = Cylinder
 Element 7 = 125.92 [MPa]
 Element 8 = 242.25 [MPa]

Outreach = 6600 mm, Lloyds Register

OVERHEAD LAUNCH AND RECOVERY SYSTEM OUTPUT DATA:
Classification Society: Lloyds
Strength Model: 2

SWL =   15000 [kg]
Calculated Load = 64318 [kg]
Upper Door Length =   6500 [mm]
Lower Door Length =   3500 [mm]
Hangar Height = 10000 [mm]
Outreach = 6600 [mm]
In reach =   4455 [mm]
Steel Weight = 28622 [kg]

Cylinder 1 Dimensions:
Index = 55 øD = 400.0   ød = 340.0 øB = 508.0 A = 1125.0 J/F = 265.0   H = 320.0 øG = 200.0 H_MIN = 280.0

Cylinder 2 Dimensions:
Index = 42 øD = 340.0   ød = 220.0 øB = 419.0 A = 1075.0 J/F = 250.0   H = 260.0 øG = 180.0 H_MIN = 245.0

Minimum Clearance = -691 [mm] OK
Maximum allowable height of ROV + TMS = 4754 [mm]

Position of cylinder wall attachment:
 y-coordinate = 4432 [mm]
 z-coordinate = -4781 [mm]

Reaction force at hangar wall = 3072.56 [kN]

Diameter of hinge pin A = 194.33 [mm]
Diameter of hinge pin D = 166.45 [mm]

Stresses:
 Element 1 = 266.10 [MPa]
 Element 2 = Cylinder
 Element 3 = 266.10 [MPa]
 Element 4 = 263.65 [MPa]
 Element 5 = 236.53 [MPa]
 Element 6 = Cylinder
 Element 7 = 151.49 [MPa]
 Element 8 = 254.11 [MPa]

Appendix B – Weighted evaluation matrix

Each concept cell shows the rating / weighted score.

Criteria	Weight	Ideal	Concept 12	Concept N 8	Concept N 5	Concept 3	Concept 6	Concept N 6	Concept N 2	Concept 15
Outreach	4	20	5 / 20	3 / 12	4 / 16	5 / 20	4 / 16	5 / 20	5 / 20	5 / 20
"Inreach"	4	20	5 / 20	2 / 8	5 / 20	2 / 8	5 / 20	5 / 20	5 / 20	5 / 20
Complicity	5	25	5 / 25	3 / 15	4 / 20	5 / 25	3 / 15	5 / 25	4 / 20	5 / 25
Interface										
LARS/Door	4	20	4 / 16	4 / 16	4 / 16	5 / 20	4 / 16	5 / 20	5 / 20	5 / 20
Maintenance	5	25	4 / 20	3 / 15	4 / 20	4 / 20	3 / 15	4 / 20	4 / 20	5 / 25
Handling	5	25	2 / 10	3 / 15	5 / 25	5 / 25	5 / 25	5 / 25	5 / 25	5 / 25
Closing hatch	3	15	5 / 15	4 / 12	4 / 12	5 / 15	4 / 12	5 / 15	5 / 15	5 / 15
Size in hangar	4	20	5 / 20	2 / 8	5 / 20	3 / 12	4 / 16	5 / 20	5 / 20	5 / 20
Distance to surface at launch	3	15	5 / 15	5 / 15	5 / 15	5 / 15	5 / 15	5 / 15	5 / 15	5 / 15
Mobility in hangar	4	20	5 / 20	3 / 12	5 / 20	5 / 20	3 / 12	5 / 20	5 / 20	5 / 20
Total		205	181	128	184	200	146	181	202	195 / 205
		1	0,883	0,6244	0,8976	0,9756	0,7122	0,8829	0,9854	0,9512 / 1

Concept 12: Vertical sliding door, Winch it from the floor to hang from on floor, OH rail, Telescopic arm, OH rail, Lower freely, Telescopic arm, movement through Vertically sliding splash-zone, Side hinged door(s), Vertically sliding splash-zone, Side door with cutout.

Concept N 8: Side hinged door(s), Winch it from the floor to hang from on floor, Slide/push OH rail, Telescopic OH A-frame, hull for vertical movement through splash-zone, Side hinged door(s), Vertically sliding door.

Concept 5: Telescoping "hatch", Hydraulic snubber manoeuvring, Slide/push on floor, Telescopic OH rail, Rails along hull for vertical movement through splash-zone, Vertically sliding door.

Concept 3: Top hinged door with arm(s) for ROV, Ulmatex OH LARS), Move fixture on OH rails, Rails along hull for vertical movement through splash-zone, Bottom Vertically sliding door with cutout.

Concept 6: Vertical sliding door, Fixture already mounted on overhead rail (ref. Ulmatex OH LARS), Winch it from the floor to hang from OH rail, Telescopic OH rail, Rails along hull for vertical movement through splash-zone, Horizontally sliding door.

Concept N 2: Telescoping "hatch", Winch it from the floor to hang from OH rail, Rails on top hinged door, OH rail, Rails along hull for vertical movement through splash-zone, Vertically sliding door.

Concept 15: Top hinged door with rails, Winch it from the floor to hang from OH rail, OH rail, Rails along hull for vertical movement through splash-zone, Vertically sliding door with cutout.