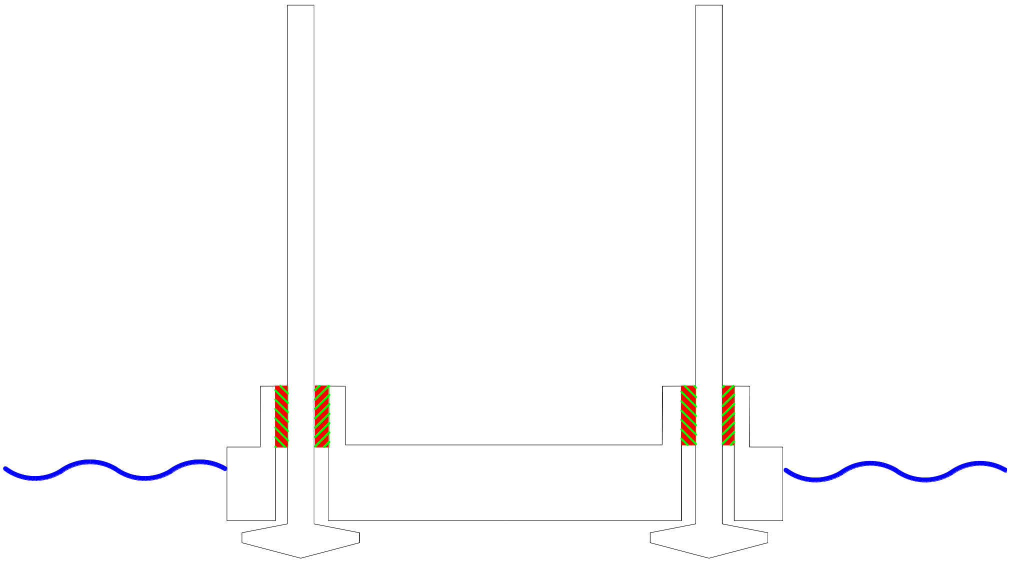
# A standstill to get further

## Leg sea-fastening system for frequently used jack-ups



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Bachelor thesis 09 June 2008 – 16 August 2008

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SBM OFFSHORE GustoMSC

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## Leg sea-fastening system for frequently used jack-ups

Attema, S. (s0115487)

Final report

16 August, 2008


Supervisor Technical University Delft: Tempel, J. van der

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Westeneng, A.

**PREFACE**

Having a standstill at the specific leg sea fastening problem for frequently used jack ups a solid fixation has been created to finish my Bachelor degree in civil engineering at the University of Twente, The Netherlands. Also a solid foundation to get further in my educational and professional career is hereby constructed.

This thesis has been conducted at GustoMSC in Schiedam, The Netherlands. GustoMSC is an engineering company with a long time experience in the offshore industry. GustoMSC has been involved with the engineering of (parts of) jack-ups, semi submersibles, heavy lift cranes and more.

Because the subject of this thesis was more close to the Technical University Delft, the supervision from the University Twente was handed over to the Technical University Delft, with reference to their cooperation in the 3TU-union. The thesis had not been completed without support of the supervisor from the Technical University Delft, Jan der Tempel.

Also without direct supervision from Peter van der Graaf and André Westeneng of GustoMSC the execution of this thesis would have been much tougher. Hereby, I want to give special thanks to these three men in special and give also a great thanks to the other people from GustoMSC and other companies who were consulted for support and shared knowledge during the execution of this thesis.

S. Attema
Schiedam, 16 August 2008

Saevis tranquillus in undis.
*Parole of William I, Prince of Orange (1533 –1584)*

**SUMMARY**

Before sailing or towing of the platform, the legs of jack up platforms need to be sea fastened in order to prevent the platform and the legs from damage due to the movements of the leg originated from waves, wind and current. Also disturbing noises and vibrations from the legs hitting the platform need to be avoided because of the crew. In this thesis a new concept for leg sea fastening is discussed in order to meet the demands set by GustoMSC as far as possible.

The thesis was conducted at GustoMSC in order to come up with a new leg sea fastening system as an alternative for the system used at Bard I platform with octagonal shaped plated legs. At Bard I sea fastening is done by pushing the leg to one side with hydraulic cylinders clamping the leg between two guides and the hydraulic cylinders. The purpose of this thesis is to come up with a solution to improve: Costs, safety, reliability, engagement time and costs and the necessary time for designing and calculation of the system.

As a result of a force analysis, section 3, the decision was made to design the system only for field transit conditions, section 3.2. This decision leads to a cheaper design, but also a design which is only suitable for field transit and hence not usable for ocean transit conditions.

Several alternative leg sea fastening systems had been designed. These have been compared to each other in section 4 with a multi criteria analysis on the demands earlier set. The chosen design from out the evaluation, is the double wedge variant. This system consists of two pairs of wedges, one pair placed at lower guide level and one pair at upper guide level. One wedge of each pair placed at the leg, the other at the jacking house. When retracting the leg the wedges run into each other by which the leg is forced sideways against the guides. The jacking house wedges all have a lubrication system for engagement to obtain an optimum wedge angle of about seven degrees for optimization of the pull out force and the force through the leg, as found in section 5.2.

However, in order to create a tight fit the upper wedge at the jacking house needs to be adjustable mounted. The choice is made for a top spacer system, section 5.3. This system contains of six adjustable M20 bolts connected to an impact plate where the wedge runs into to create an adjustable connection. For disengagement the wedge can run into a console placed lower.

Because of the guides the upper wedges cannot be placed on the stiffest parts of the leg, and should hence be placed on the leg hull, due to this the leg needs to be stiffened with the triangle shaped stiffening as described in section 5.4. This consists of two HE340A beams of 4.2 meters long and 2 extra stiffeners of the leg hull. These stiffeners are placed behind the wedge.

For comparison the double wedge system was compared with the existing Bard I system. All concluded the features for improvement were partly met, as discussed in section 6.

- When costs will be referred to as weight the double wedge system might improve this (+).
- Both systems would not cause great safety hazards (+/-).
- Reliability might improve due to less moving parts, but overload should be prevented (+/-).
- Engagement time and costs are reduced because the system is passive (+).
- Calculation time however will increase because of the stiffening of the leg and calculation of the wedges would be more difficult than calculation of the jacks used on Bard I (-).

The systems complexity of the sea fastening system would increase when choosing the double wedge system in exchange of faster and cheaper engagement.

## THESAURUS

| Terminology[1] | Explanation |
|---|---|
| Catch beams | Hydraulic jacking system with large rings or beams around the leg acting like a hand over hand system. |
| c-c | Center to center. |
| CJ | Class of drilling jack ups designed by GustoMSC. |
| DNV | Det Norske Vertitas, classification institute. |
| Field transit | Transportation at very short distance (no longer than 12 hours, see also Bennet and associates L.L.C. (2005)). See also Ocean transit. |
| Germanischer Lloyd | Classification institute. Also: GL-group. |
| Guide | Piece of metal used to guide the leg through the hull. |
| Jacking house | Part which houses the jacking equipment. |
| Jacking system | System used to raise the platform and retract the leg. See also catch beams, pin and hole and rack and pinion. |
| Leg | The long beams the platform stands on. |
| Leg hull | Weak part of a leg section used to connect the racks. |
| LSFS | Leg sea fastening system. |
| MCA | Multi criteria analysis. |
| M-S-N-lines | Bending moment, shear force and normal force lines. |
| Ocean transit | Transportation method of jack-up at long distance (longer than 12 hours, see also Bennet and associates L.L.C. (2005)). See also Field transit. |
| Pin and hole | Hydraulic jacking system using a pin connected to a yoke which is pushed through holes in the leg. When connected the leg is moved a bit. The yoke is again taking the pin out enabling the next move. |
| Pitch | Rolling motion along the long platform side. See also Roll. |
| Platform/ hull/ vessel | The part of the structures for operational use and housing of the crew, also the structure to mount the LSFS onto. |
| Rack | Thicker and stiffer part of the leg which carries the jacking loads. |
| Rack and pinion | Jacking system with a rotating pinion running along the toothed rack along the leg, mostly used for truss legs. |
| Roll | Rolling motion along the short platform side. See also Pitch. |
| Spudcan | Lower box type part of the leg for support on the seabed. |
| Yoke | Piece of the pin and hole system which connects the pin to the jacking cylinder. |

[1] See also: Figure 1: Jack up elements

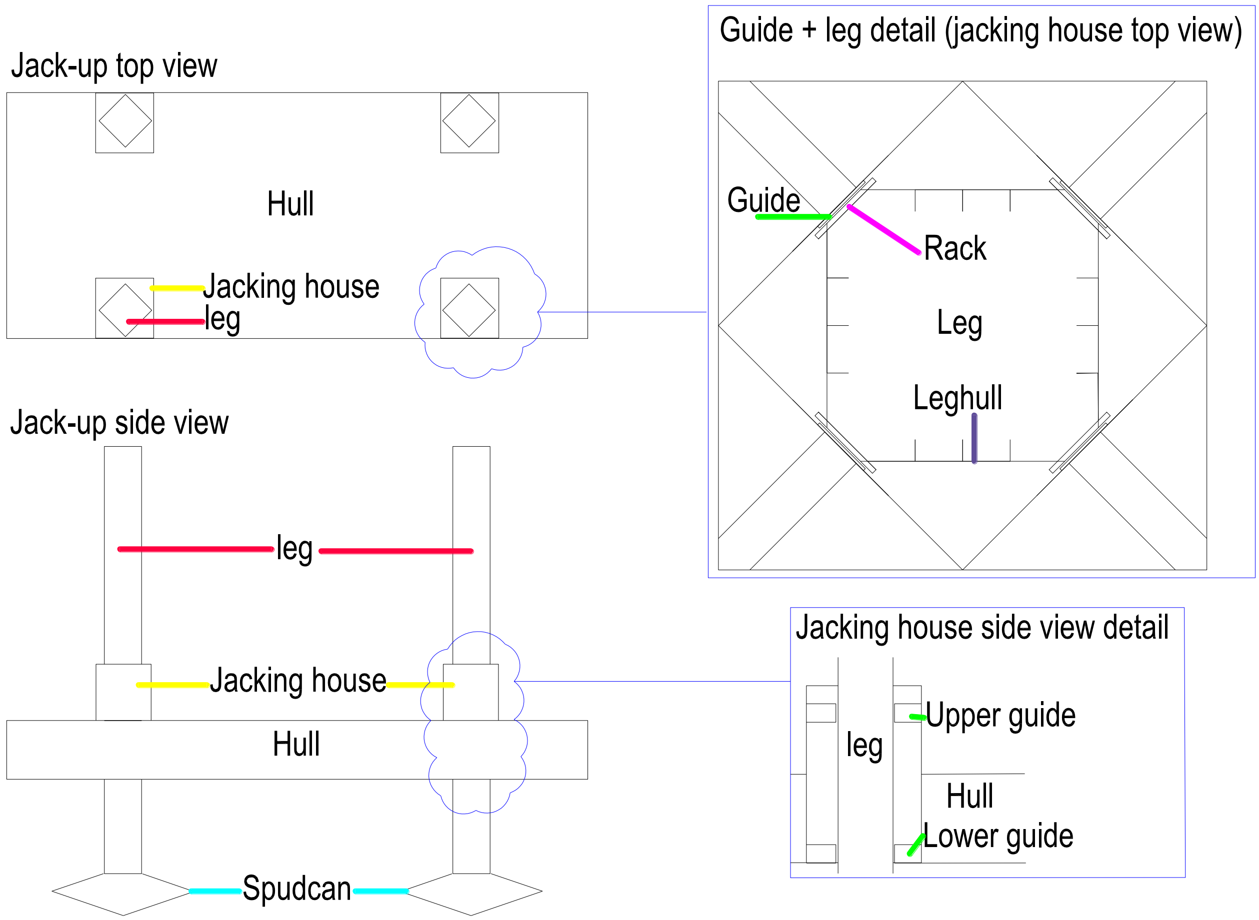



Figure 1: Jack up elements

## EXPLANATION OF SYMBOLS

| Symbol | Description | Standard unit |
|---|---|---|
| *A* | Area | $m^2$ |
| *b* | Width | m |
| *c* | Coefficient | - |
| *d* | Depth | m |
| *D* | Diameter | m |
| *E* | Modulus of elasticity | $N/mm^2$ |
| *F* | Force | N |
| *f* | Yield strength | $N/mm^2$ |
| *g* | Gravitational acceleration | $kg*m/s^2$ |
| *h* | Height | m |
| *I* | Moment of inertia | $m^4$ |
| *k* | Spring stiffness | N/m |
| *l* | Length | m |
| *M* | Bending moment | Nm |
| *m* | Mass | kg |
| *n* | Amount/ number | - |
| *r* | Radius | m |
| *T* | Period | s |
| *t* | Time | s |
| *V* | Volume | $m^3$ |
| *v* | Speed | m/s |
| *w* | Bending distance | m |
| *W* | Moment of resistance | $m^3$ |
| *z* | Distance | m |
| *α* | Angle | $^o$ |
| *γ* | Safety coefficient | - |
| *Δ* | Change | - |
| *θ* | Motion angle | $^o$ |
| *ρ* | Specific mass | $kg/m^3$ |
| *σ* | Stress | $N/mm^2$ |
| *φ* | Bending angle | $^o$ |

# Contents

## 1. INTRODUCTION

The market for offshore wind farms is booming today. More and more wind turbines are placed or planned in offshore areas. Special offshore installation platforms and vessels are designed to install these wind turbines. Most platforms used for this purpose are jack-up type platforms. These are offshore platforms able to float to a specific location and then lifting themselves out of the water with their jacking system, as shown in Figure 2. When the platform finishes its job the platform is again lowered in the water and the legs are fully retracted, see Figure 3.

Jack ups could be divided by the way they lift themselves. Several jacking systems are in use: Rack and pinion which continuously uses a rotating pinion which rotates along a rack along the whole leg. Catching beams are large sections grabbing the leg at several heights, acting like a hand over hand system. It is also possible the legs are controlled with cables and winches which is only suitable for shallow waters. The last option is the pin and hole system which uses holes in the legs rack where a pin from the jacking system can be pushed in so the jacking system can lift the leg bit for bit.


Figure 2: Jack-up construction vessel Smit Lisa, lifted, mention the gap between platform and water level; ref. www.smit.com

Figure 3: Smit Lisa, towed, mention the retracted legs; ref. www. tugspotters.com

For windmill installation jack ups are used because of the short project time, which requires the platform to be able to move from one site to another. The variability in the loads due to the lifting operations requires the platform to stand stable on the seabed and hence a ship would not be preferable.

To become more profitable those platforms need to install turbines as quick as possible. A time consuming task a board this platform type is securing the jack-up legs before sailing, this is called leg sea fastening. This needs to be done to prevent the legs and the platform from damage and to avoid inconvenient noises and vibrations from the legs hitting the platform. Noise and vibrations need to be avoided because of the crew. This movement of the leg is possible because a gap exist between guides and racks, to be able to retract and lower the leg. However this gap is small, about 20 to 30 mm, the problem is large enough to cause the problems.

Formerly this “sea-fastening” was done by hand by means of shimming wooden blocks between the legs and the guides. Since this is a time consuming task and needs to be done very often because of the, relatively, short project time, the hand wise system has to be replaced by a less time consuming system.

An existing leg sea fastening system (LSFS) designed for the construction platform Bard I is an expensive solution so GustoMSC would like to invent a creative alternative to this. This means a leg sea fastening system for octagonal shaped plated legs with a pin and hole jacking system. Hereby the following aspects should be considered and should be improved as much as possible: Costs, safety, reliability, engagement time and costs and the necessary time for designing and calculation of the system.

***This thesis spans:***

- The basic design of a LSFS for octagonal shaped plated legs with pin and hole jacking systems,
- with the loads established according to the requirements set by the GL-group (Germanischer Lloyd).
- by making use of the requirements set for and the sizes of the Bard I platform,
- with some basics of loads applied to the jacking house structure,
- and the comparison of this design to existing systems on the given aspects.

***This thesis does not span:***

- A complete analysis of the effect of the LSFS on the structure and handling of the ship, and for that reason no FEM-analysis (finite element analysis) of the structure,
- also not the loads applied from the jacking house to the rest of the vessel,
- and no calculation of the load resistant capability of the jacking system for the vertical forces endured by the own weight of the leg.

The existing systems were put under search at first in order to gain knowledge about the variety of solutions already available. Also the loads which apply to the fastening system needed to be established before the actual design could take place. From this solid basis it was possible to create several alternatives. These alternatives have been compared to the features set in the demands. After being chosen as the best alternative, the double wedge system was further elaborated on some crucial elements.

This document creates a foundation for a new type leg sea fastening system. With this thesis it is possible to get the design of frequently used jack ups further by having a standstill, establishing a creative method to bring a standstill to the leg movements when the jack up needs to get further.

## 2. COMPARISON EXISTING LEG SEA FASTENING SYSTEMS

*Before the actual design of a new leg sea fastening system can begin it is necessary to get insight in all existing systems with their properties. Several systems are in use to secure legs to the jack up platforms before towing or floating. Most existing systems are compliant with the rack-and-pinion jack up system which is commonly used at truss type legs. This system works with a rotating pinion driving a tooth rack placed along the complete length of the leg. Because of the long stay of such platforms at one site, the fastening system is mostly also used as fixation system for the operational period to relieve the jacking system. An easier principle, which is also in use for platforms which remain on the same location for a longer period of time, is by means of shimming wooden blocks in the gap between the leg and the platform. The third solution discussed is used at the Bard I. At this vessel, with a pin and hole jacking system, the legs are pushed to one side for sea fastening. The last system is those from the Mayflower Resolution. This system, compliant with a catch beam jacking system, is described because it works with square shaped, plated legs. Several aspects per system are mentioned in the tables.*

### 2.1 RACK FIXATION

*Several leg sea fastening systems are designed for truss legs, with various shapes. Most of those legs are jacked with a rack and pinion system. So for fastening rack fixation systems could be used. These systems are using a counter rack which is pushed into the rack of the leg securing it to the platform.*
*Various types of rack fixation systems have been designed, but all are based on the same principle, as outlined above. First to mention is the CJ-fixation system which was designed by GustoMSC which uses vertical adjustment to position the teeth. The second and third systems are mentioned here to show the variety of solutions: The first which works with adjustable teeth, the third which works with a pivot.*

#### 2.1.1 CJ-fixation system

A sea fastening system designed by GustoMSC is called the CJ-fixation system as described in GustoMSC (n.d.), this system is used at several CJ-class jack-up rigs. This system is so far only used on triangular shaped truss legs, but is only limited to rack driven legs. The reason for this is the working of the system with the rack jacking system of the rig. The system contains of a pair of counter racks which are operated by a hydraulic system and pushed into the racks of the leg by other hydraulic cylinders. When disengaged (see Figure 4) enough spacing is available to hold off the legs from the fixation system by the guides. When engaged the forces and bending moments are transferred by a combination of vertical and horizontal forces.

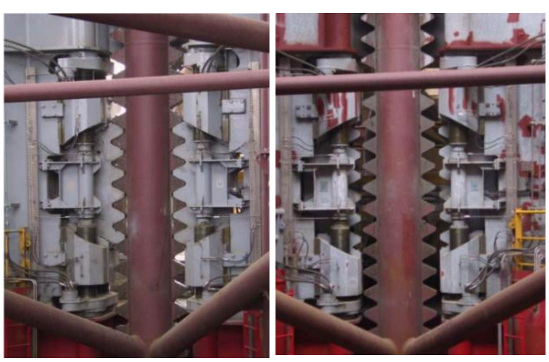
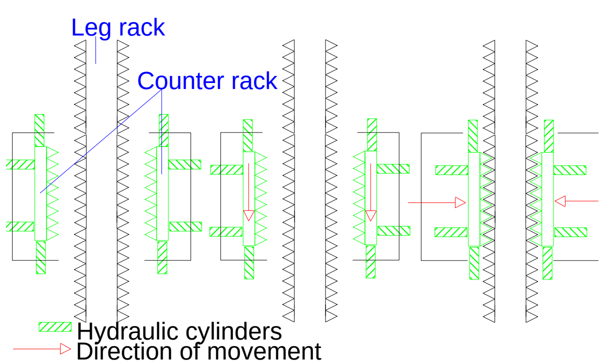


Figure 4: CJ fixation system, e (l), e (r)




ure 5: CJ fixation system, d(l), alignment (m), e(r)

How this works is illustrated in Figure 5. The system is controlled by one person and takes only one hour per leg. A major advantage is the possibility to fixate the system at all heights. A major disadvantage is the use of several cylinders (for the positioning and the engagement) which reduces reliability.

| Item | Value | Unit |
|---|---|---|
| Leg types | Rack driven (mostly truss, triangular shaped) | |
| System | 2 | Counter racks per rack |
| Control | 1 | Person |
| Operation | 1 | Hour/ leg |
| Fixation when operable | Yes | |

Table 1: Specifications, CJ-leg fixation system

### 2.1.2 Offshore jack-up rig locking system

An alternative to the CJ-fixation system is given in WIPO (1992). This system claims to overcome the problem of imperfections in the racks by pushing singular “teeth” (so called locking bars) into the rack one at a time so every tooth connects perfect to the rack. A minor problem has been overcome with this, however a major problem arises: more moving parts resulting in less reliability.

| Item | Value | Unit |
|---|---|---|
| Leg types | Rack driven (mostly truss) | |
| System | 2 | Counter racks per rack |
| Control | 1 | Person |
| Operation | Estimation according to CJ: 1 | Hour/ leg |
| Fixation when operable | Yes | |

Table 2: Specifications, Offshore jack-up rig locking system

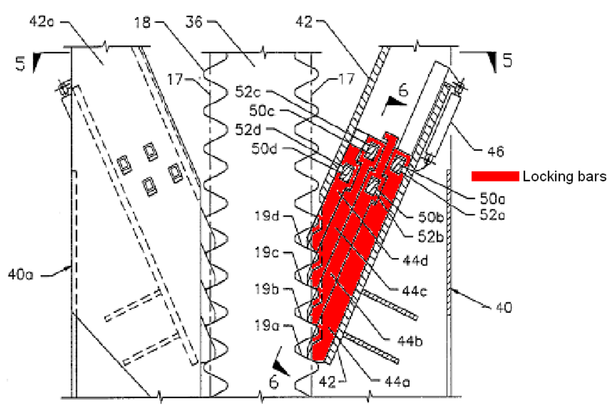



Figure 6: Offshore jack-up rig locking system: engaged

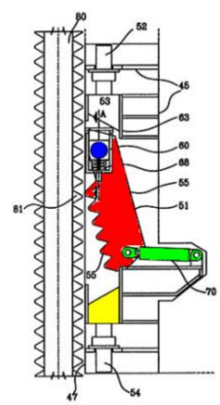


Figure 7: Self positioning fixation system: disengaged

### 2.1.3 Self positioning fixation system

Another variety in rack fixation systems is the one described in WIPO (1997). This system contains of a counter rack (red) which is able to rotate about a pivot (blue) and controlled by a hydraulic jack (green) as shown in Figure 7. From below a wedge shaped piece of metal (yellow) is used to fixate the system. Major advantage is the self controlling system; it is able to align itself with the rack. Another advantage is the fixation from below.

| Item | Value | Unit |
|---|---|---|
| Leg types | Rack driven (mostly truss) | |
| System | 2 | Counter racks per rack |
| Control | 1 | Person |
| Operation | Estimation according to CJ: 0.75 (no alignment needed) | Hour/ leg |
| Fixation when operable | Yes | |

Figure 8: Specifications, Self positioning fixation system

## 2.2 WOODEN BLOCKS

Traditional jack-up legs are fixated to the platform by means of shimming wedge shaped wooden blocks in the gap between the guides and the legs as shown in Figure 9. This is a time consuming task. Major advantage is the price of the system. Only wooden blocks have to be paid. The capabilities of the guides are used to transfer the forces and bending moments from the legs to the vessel.

Other advantages are the possibility to use this system at various types of legs and the possibility to use the system at almost every height. Major disadvantage is the possibility that the blocks can get jammed by the movement of the legs. This makes it difficult to disengage the system.

| Item | Value | Unit |
|---|---|---|
| Leg types | All | |
| System | 1 | Block per rack |
| Control | | |
| Operation | | |
| Fixation when operable | Yes | |

Table 3: Specifications, wooden blocks

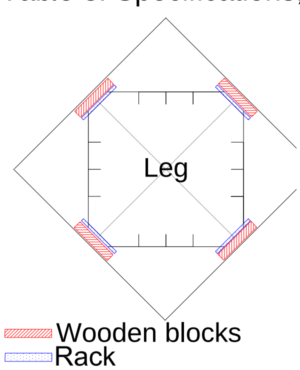



Figure 9: Wooden blocks: engaged

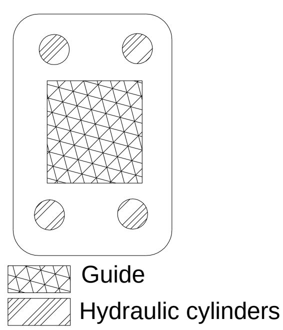



Figure 10: Bard I LSFS front view

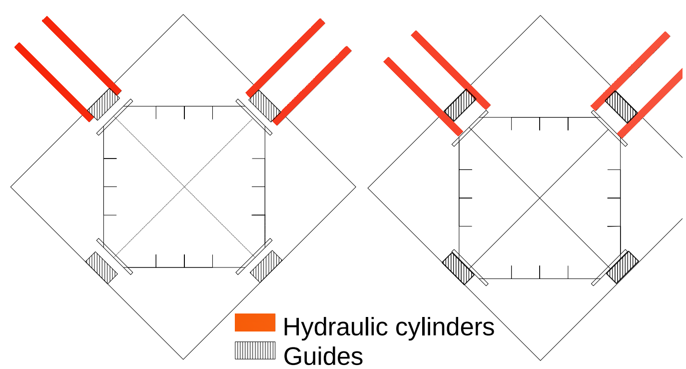



Figure 11: Bard I LSFS top view: disengaged (l), engaged (r)

## 2.3 THE BARD SYSTEM

For the Bard I windmill installation platform, a system was designed to overcome the gap between rack and guides by pushing the leg against the opposite guides. The system works with 8 cylinders, 2 above each other which were placed above and under the upper guides as shown in Figure 10. How this works is illustrated in Figure 11 where the left drawing is the disengaged system and the right drawing is the engaged system. Major disadvantages of this system are the costs, originated from the 8 cylinders, and the fact that the legs are fastened under an angle so the system cannot be used when operational. The well defined loads and the possibility to engage at every height and the relatively short engagement time are advantages.

| Item | Value | Unit |
|---|---|---|
| Leg types | Square plated | |
| System | 8 | Cylinders per leg |
| Control | 1 | Person |
| Operation | Estimation according to CJ: 0.5 (no alignment needed) | Hour/ leg |
| Fixation when operable | No (Fastening with angle) | |

Table 4: Specifications, Bard I LSFS

## 2.4 THE MAYFLOWER RESOLUTION SYSTEM

For the windmill installation vessel Resolution, formerly owned by the Mayflower Energy ltd. Company, a leg sea fastening system was designed by GustoMSC. The Resolution is equipped with six square shaped plated legs. The system contains of eight hydraulic cylinders per leg, two above each other, pushing the square leg against the opposite upper guides, as shown in Figure 12. Difference with Bard I is the racks are placed as cantilevers outside the legs for use with the catch beam jacking system. Thereby it is possible to push the leg in line with the leg hull (at Bard I the pushing is done with an angle). The lower sea fastening, as shown in Figure 13, is done by hauling the leg up against the lower guides forcing it to move sideways because of the shape of the guides in combination with the shape of the spudcan. Major advantages of this system, above Bard I, are the aligned forces, resulting in an easier to control system.

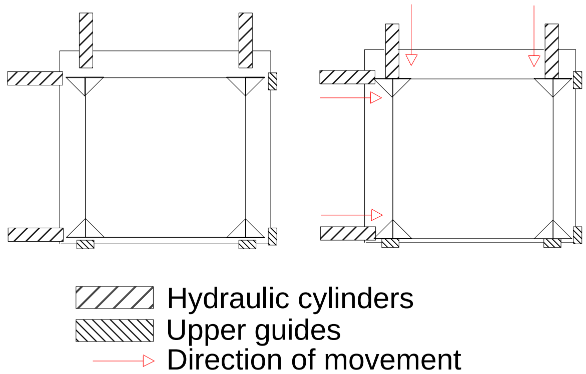



Figure 12: Mayflower Resolution upper LSFS top view

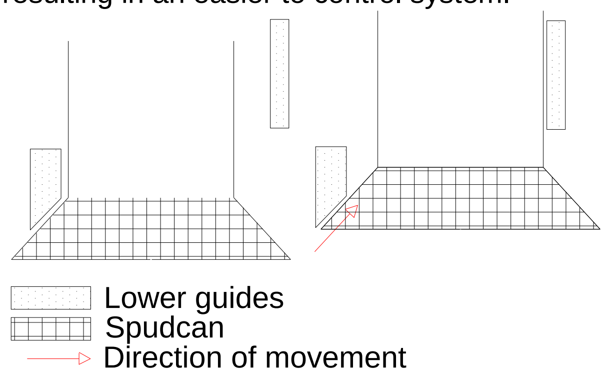



Figure 13: Mayflower Resolution lower LSFS, side view

| Item | Value | Unit |
|---|---|---|
| Leg types | Square plated | |
| System | 8 | Cylinders per leg |
| Control | Estimation based on Bard I: 1 | Person |
| Operation | Estimation according to CJ: 0.5 (no alignment needed) | Hour/ leg |
| Fixation when operable | No (Lower fixation not possible) | |

Table 5: Specifications, Mayflower Resolution LSFS

# 3. FORCE ANALYSIS

*Before alternatives could be discussed it is practical to discus some basics behind the forces affecting these alternatives. It is also practical to present some outcomes of this detailed force analysis which were used in the alternative generation. The detailed force analysis can be found in section 11.2. Also a decision has to be made what applies to the new design, ocean or field transit conditions.*

## 3.1 GENERAL FORCE ANALYSIS

The forces affecting the jack up platforms are exerting from wind, waves, current, its own weight and also inertia due to roll and pitch motions of the platform. All these forces are combined in a calculation method proposed by Det Norske Veritas (1992) which formulas are also given in section 11.3 with the used symbols outlined in the drawing of the platform in section 11.4. This calculation results in a bending moment as outlined in Figure 14. This bending moment is distributed along the fixation points, either two or three, with the formulas outlined in section 11.2.3 and 11.2.4

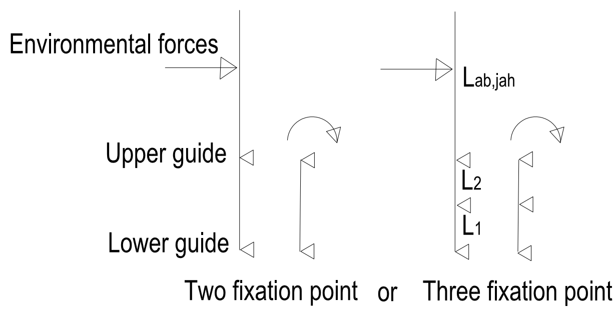



Figure 14: Force analysis, mechanical drawings

Within the force analysis a difference should be made according to the transit conditions used: field transit (movement under 12 hours) or ocean transit (12 hours or longer). Also a difference can be made according to the motions of the platform: pitch or roll. The difference to forces in the guides with respect to these conditions can be described according to Table 6.

| | Pitch | Roll |
|---|---|---|
| Ocean | 5 | 2.5 |
| Field | 2 | 1 |

Table 6: Relations between conditions

During the force analysis all forces in the upper, middle and lower fixation point were calculated with respect to the length of the leg above jacking house $L_{ab,jah}$. When analyzing the data from the two fixation point analysis the maximum and minimum horizontal forces for field roll lays between 1.4MN and 9.0MN. The lower guide forces for field roll are between -1MN and -8MN.

The analysis of three fixation points is somewhat more difficult due to the extra degree of freedom, the extra variable $L_{1,}$ the distance between the lower and the middle fixation point. Reason for the application of three fixation points instead of two could be lack of space. The forces for three fixation points however are larger than for two fixation points. An extra bending moment is introduced due to the extra fixation point and will increase the forces in the fixation points accordingly. Though three fixation point arrangements could carry some design possibilities or are easier to implement.

## 3.2 TRANSIT CONDITIONS

*To conduct calculations to alternatives the decision has to be made which conditions apply. In general, but especially in the rules set by Det Norske Vertitas (1992), a distinction is made between ocean transit and field transit, as also cited in section 11.2.*

The main difference between the transit conditions can be found in the actual forces in the guides which distinctions were tabled in the previous section. To develop a new system the difference in ocean and field forces (about 45%) may be crucial. Major advantage of the ocean transit conditions would be the possibility to tow the platform at almost every condition; however the design may be far more expensive.

The main difference between ocean and field tow for the fixation system can be described as the forces arising from these conditions. However the main reason to choose a design condition should be the operational specifications of the platform. When referring to the definition of ocean and field tow, the distinction between them is made between a tow lasting no longer than 12 hours and a tow longer than 12 hours.

The main application of the sea fastening system under design will be the sea fastening during field tow, because of the relatively small voyages between projects. For example: the Bard company is installing wind mill farms offshore. These farms are situated no further than 100km offshore[2]. To reach shore, the installation platform should not take longer than 12 hours. The distance between the windmills is far less. Although the system is not exclusively designed for the Bard Company, the example shows the main application of the system.

Due to the large difference in forces it is decided here to design the sea fastening system *only for field transit*. The decision does not leave out ocean transit, but it points the focus to field transit. Ocean transit should in that case, if necessary, be conducted by traditional ways, e.g. wooden block method. Ocean transit however should always also be considered. If an alternative has to be chosen, the possibilities for ocean transit should also take part in the decision. Additional calculations can be made what differences to the system would transfer it into an ocean transit sea fastening system.

[2] Shore side of BardNL1 = 60km offshore (www.bard-engineering.de).

# 4. ELABORATION OF PRINCIPLES

*In order to come up with creative solutions for the leg sea fastening problem it was necessary to conduct a survey to establish a great variety of alternative principles. In attachment 11.7 possible driving and clamping techniques are shown which were found during the survey. In attachment 11.10 "Field of search, principles", the systems are used to create principles and alternatives. Due to the large number of alternatives a preliminary selection had been made. Selection of principles for elaboration was made with use of a multi criteria analysis as was outlined in Attachment 11.10.3.*

*In order to choose between the seven remaining principles some basic features of the alternatives are established according to the outcomes of the force analysis, section 3. The mayor pitfall of the design is the most important feature, because this could result in a radical change of the alternative. Some other basic features are arising from the demands set for the design as described in section 1; the key elements of the system, some detailed descriptions of the calculation and engagement time, more detail about the reliability and remarks about the possibility to change the systems design conditions into ocean transit conditions. These features are described in section 11.16. In this chapter only their outcome are given and the main feature: Pitfall. The choice which alternative should be taken for elaboration was made with making use of a multi criteria analysis. For the multi criteria analysis at the end of this chapter the following features and scores were used.*

***Decision remarks:**[3]*

- *Pitfall (weight: 10):* — *Feasibility of the system: 0 = unfeasible, 1 = difficult, 2 = feasible.*
- *Calculation time (weight 1(leg), 0.5 (jacking house), 0.5 (system)):* — *0 = major adjustments, 1 = substantial, 2 = intermediate, 3 = minor, 4 = no extra calculations.*
- *Engagement time (weight 5):* — *Quantified.*
- *Reliability (weight 3):* — *Scale: unreliable 1 – 10 reliable.*
- *Ocean transit (weight 2):* — *1 = major adjustments, 2 = doubling the system, 3 = minor.*

## 4.1 RACK ENCLOSURE

The principle of rack enclosure is based on the CJ-fixation system. This system, as described in chapter 2.1.1, is suited for rack and pinion jacking systems. Although the jacking system used in jack-ups for which the new sea fastening system is designed is of the pin and hole type, the arrangement of CJ is suitable. CJ clamps the racks at two opposite sides, with rack enclosure this is done by pushing against the sides of the racks. This is made clear in Figure 15. Major advantage of this system, compared to Bard I, is the fact that forces are exclusively carried by the racks and the leg is kept straight. Major disadvantage is the large amount of moving parts. Difference with the CJ system will be the bending moments which are not carried by vertical forces.

### Pitfall

The major pitfall of this alternative will be the alignment of the cylinders when the leg is inclined. This means the effective pushing area of the bars, the pieces of metal connecting cylinders at

[3] Calculation time is an indication of the complexity of the design. Ocean transit is an indication of the necessary adjustments to the design to meet ocean transit conditions. Hence doubling the system means the necessary adjustments require twice as much material or twice as strong materials as the proposed system.

the same rack side, will be smaller than the surface area of the bars, see also Figure 16. However this might be possible as in detailed outlined in 11.11.

**Description:** The system contains of two hydraulic cylinders which are pushing a metal bar against the sides of the racks of the leg. By doing so clamping of the racks between the two bars will be established. This is in detail drawn in Figure 16.

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 2 | 4 | 3 | 3 | 30 s | 6 | 2 |

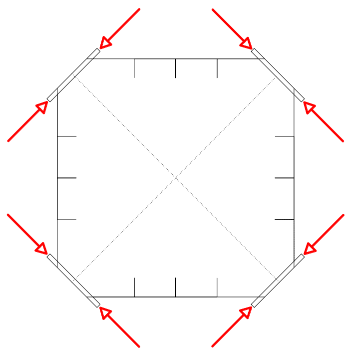


Figure 15: Rack enclosure, principle

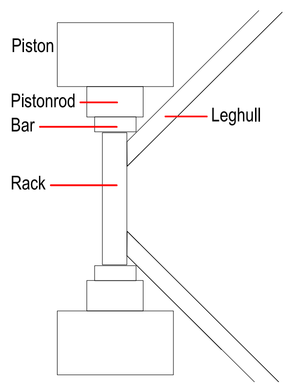



Figure 16: Rack enclosure, rack detail

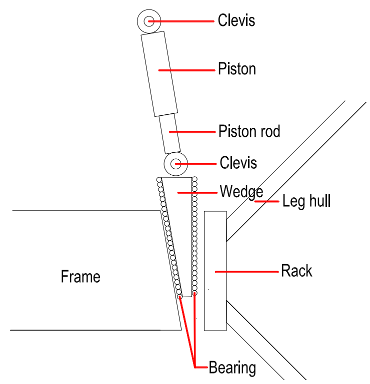



Figure 17: Wooden block detail sketch

## 4.2 WOODEN BLOCK VARIANT

The principle of the wooden block variant consists of a solid piece of material, e.g. wood or steel, which is forced between leg and guides. This can be done by rotating it in or by lateral movements. Advantage is, when engaged the forces can be driven through the block and guides instead of the driving system of the sea fastening system. Major disadvantage will be the force needed to disengage the system when the wedge gets jammed.

### Pitfall

Major pitfalls of the wooden block variant would be engagement and disengagement of the system. When the legs are inclined there is no gap left between the guides and the racks, so pushing in the blocks might get difficult. More-over the system, as described in attachment 11.10.1, by rotating in the solid might cause large local stresses at the tip of the wedge and large bending moments in the lever. When the system needs to disengage the wedges could get jammed by the movements of the leg which might cause disengagement difficulties.

One solution to the problem might be not to use the guides, but a piece below, between and/ or above the guides shaped as a wedge. Along this a wedge is forced “upward”, pushing the leg with a lateral movement as shown in Figure 17 (to prevent from bending moments in the lever). Advantages are the aligned forces through the racks, the relatively small forces in the driving system and the fact that it is not necessary to force the wedge in the gap because the wedge is already in front of the rack and needs only to be slid in. Disadvantage is the extra structure needed along the guides. By using bearings at both sides of the wedge it might be possible to reduce shear stresses, mostly arisen from the engagement of the system.

The force in the hydraulic cylinders can get 8575kN when disengaging at maximum stress level and 2095 kN when engaging. The calculation of this force is derived in 11.12. Engagement would imply the use of one standard cylinder with a 320mm piston diameter[4]. But disengagement needs four of those or two 450 mm pistons[5]. The large disengagement force could be overcome by making use of the jacking system.

**Description**
By means of extending the piston rod a wedge shaped solid is pushed in the gap between the "track/ frame" and the rack of the leg forcing the leg inwards as shown in Figure 17.

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 2 | 4 | 2 | 2 | 81 sec. | 9 | 2 |

## 4.3 LEG CLAMP

The basic principle behind this variant is to spread the forces arisen from the environment over the complete surface of the leg and jacking house by using a large shape as clamp. The spreading of the forces is thereby the major advantage. Major disadvantages are the size of the system and possible concentrated stresses. An idea about the principle can be found in Figure 18, where clamping is generated by sliding in the two red solids.

**Pitfall**
Mayor pitfall in the clamping system will be its own advantage. The reason to choose for the clamping system is its surface area. Because the clamp surrounds the whole or at least the mayor part of the leg, the clamp is able to spread the forces arisen from the environment along its surface. In practice problems may arise from imperfections or rotation of the leg. This is made clear in Figure 18; the green dots are the local points where concentrated stress will arise when a slight rotation of the leg occurs. Another problem arises from the support of the clamp which would again result in concentrated stresses.

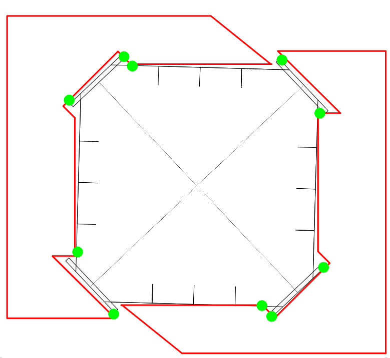


Figure 18: Leg clamp stress points

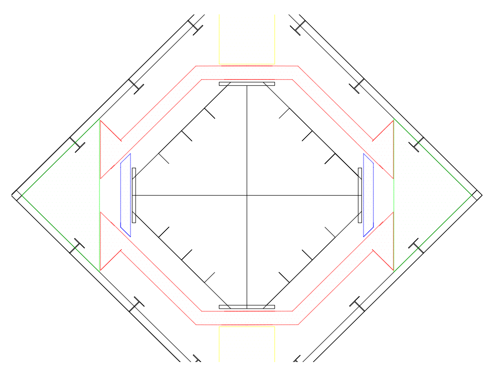


Figure 19: Leg clamp, variant 2 sketch

[4] Maximum of 2574kN at 320 bar, according to Mannesmann Rexroth (n.d.).
[5] With a maximum of 5089 kN at 320 bar, according to Mannesmann Rexroth (n.d.).

These disadvantages require the system to be used in a slightly different configuration. The forces will thereby only be transferred to the racks but the engagement is still done from two sides, and is hence possible by using two jacks from the jacking systems which are not in use during transit. A sketch is given in Figure 19. The red beams are the activators which could be driven by the yokes. The forces from the opposite racks are driven through the blue wedges to the red beams. The problem here is the displacement of the red beams, acting like a cantilever with 5MN of force. When these are taken as HE1000M beams displacement would still be at least[6] 70 mm, which would be the largest beam which can be applied in the available space.
The solution would be to hinge the long beams to create just axial forces. The problem here would be the change of direction of the movements at the non-yoke-driven racks. A solution can be found in the use of a two side wedge system as drawn in Figure 20. One rack is clamped directly by the wedge. The other racks are fixated through a hinged connection as outlined in Figure 21. The maximum pulling force of 5MN can be applied through a cable or bar. Problem of this option would be the large amount of metal and moving parts involved, and hence the large weight of the system and reduced reliability.

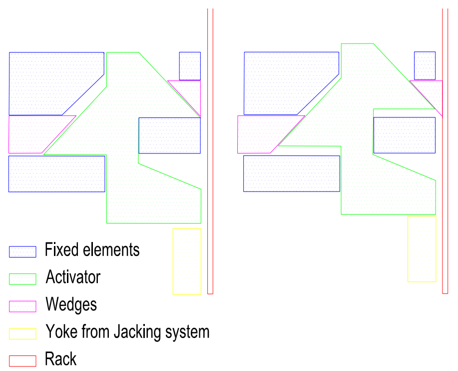


Figure 20: Clamp activator

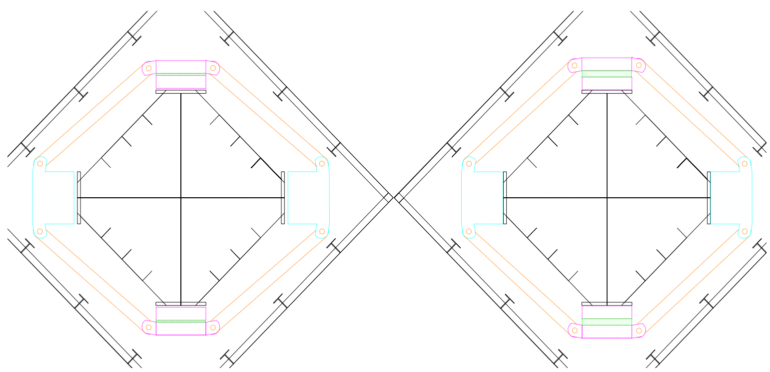


Figure 21: Leg clamp, variant 3 sketch

**Description**
With a at two sides triangle shaped activator opposite wedges are activated. One of them clamps a rack directly; the other activates two clamping blocks at other two racks. The pushing could be performed by the yokes of the jacking cylinders. Thereby the leg is clamped at its four racks.

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 2 | 4 | 2 | 1 | 50 sec. | 9 | 2 |

## 4.4 DOUBLE WEDGE
The Mayflower lower sea fastening system, as described in section 2.4, consists of a wedge shaped piece of metal which forces the spudcan aside. This principle can be repeated at the upper guide. Major advantage is the system does not have any extra driving units. Major disadvantage can be disengaging a jammed wedge and the alignment of the upper and lower wedge. The application is shown in Figure 22.

[6] $w = \frac{F*l^3}{3EI} = \frac{5E6*4000^3}{3*2.1E5*722300E4} = 70mm$

**Pitfall**

The mayor pitfall for this passive alternative will be, due to the fact the system is passive, the alignment of the wedges. In theory it is possible to align these correct. Trouble though arises from a slight bending of the leg or the wedges, a possible margin from construction or some imperfections due to wear of the legs and fastening system. Another problem is the existence of the jacking system and the lower guides, hence it is not possible to locate the upper wedges on the racks or the upper wedges need to be located under the reach of the yokes around the side of the racks (because the front face is limited by the lower guides).

The problem though would be the alignment between the upper and lower fastening structure. A solution to the margins may be found when the upper fixation is taken as a roller. When the leg is retracted the wedge of the leg catches the wedges with the roller. Due to the movement of the leg the roller wedge is pushed upward when the leg leans against the roller or forced downwards with its own weight when the leg applies force to the opposite side. When fully retracted the wedges are complete opposite each other as given in Figure 23. To ensure the wedges stick together the combination of friction coefficient $c_w$ and the angle of the wedge $\alpha$ need to be $\alpha > tan^{-1}(\gamma \cdot c_w)$ [7] with $\gamma$ as a safety coefficient. This formula is outlined in attachment 11.12.

The second pitfall requires the leg structure to be stiffened or the placement of the wedges below yoke reach. When referring to Bard I, the force at upper guide level might get 1E7N, this means with a maximum distance between the jacking cylinders of 1000mm an effective contact height of:

$h_{eff} = A/l = (F/\sigma_{s355})/l_{bet,cyl}$ = (1E7/355)/1000 = 28mm

This is very small and therefore possible to implement. It is a mayor disadvantage the leg has to be stiffened at this position because the hull would not be able to resist this force.

If the option is taken to position the wedges below the yokes, at the side of the racks the distance $L_1$ (distance between lower guide and middle fixation point) would be 1 meter and the horizontal force would be at field pitch 35.4MN, according to the force analysis in section 11.2, so with a width of the racks of 75mm this would mean:

$h_{eff} = A/l = (F/\sigma_{s355})/l_{rack}$ = (35E7/355)/75 = 1300mm

This is difficult to implement, but also fixation at the upper guide is not ensured. This means the placement of the wedges on the leg hull is preferable. Although stiffening of the leg is obligatory, the fact the system does not need any additional driving units could make it a good solution.

[7] Calculation is rough for use here, more detailed calculation can be found in section 5.2

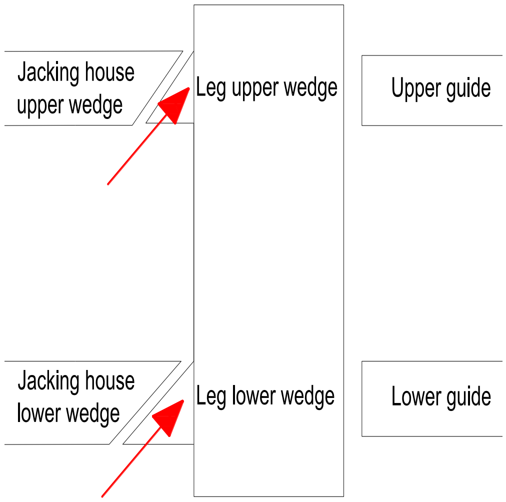



Figure 22: Double wedge principle

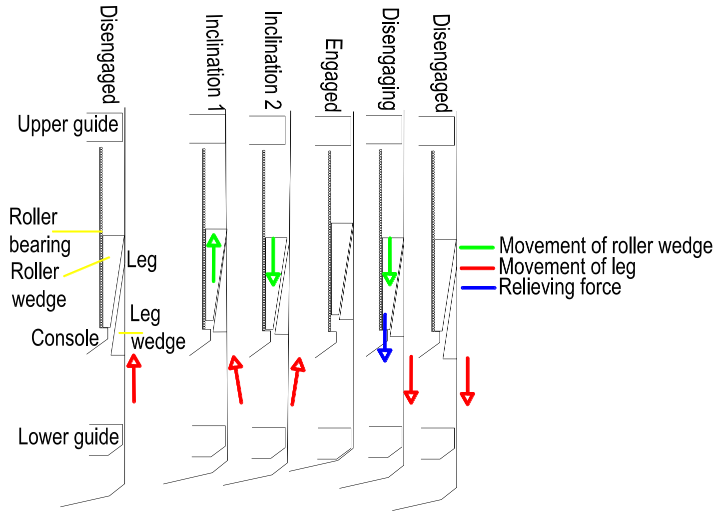



Figure 23: Double wedge, (dis)engagement steps

**Description**

When the leg is retracted by the jacking system, the lower side of the leg is fixated by pushing the spudcan against the lower guide. The upper fixation is established by sliding a wedge against an opposite one, also by the movement of the leg originating from the jacking system. This opposite wedge is able to move freely along rollers in the vertical direction. Through this it is possible to overcome the problem of the alignment between both fixation systems.

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 2 | 2 | 3 | 2 | 0 sec. | 9 | 2 |

## 4.5 BAND CLAMPING

The principle of band clamping is based on the Bard I leg sea fastening system, as described in section 2.3, which uses cylinders to force the leg sideways. The same is possible by means of tensioning a band or rope surrounding the leg and thereby forcing it towards the guides. The tensioning can be done by something like a winch or possibly a linear motor like a cylinder (because the winching distance will be short. Care has to be taken to prevent torsion of the leg and, when applied, the cylinder. A generic idea of the system is given in Figure 24.

**Pitfall**

Mayor pitfall of the band clamping design would be torsion of the leg and the possibility to damage the leg due to concentrated stresses. Torsion of the leg can be solved by pulling the band at two sides at a time or allowing a the rope to run around the leg without the rope getting caught by the leg.

Concentrated loading should be prevented. This can be solved by means of using a wider band. Trouble although arises from the corners of the racks (instead of rounded curves). Possible solution here would be change the first design, only with a band, with a stiff structure at the back of the legs, so the force would still be spread out. However the system should be controlled by a winch to prevent the system from being the same as Bard I.

Another solution is to make use of “guiding shoes”, which are stiff structures only located at the location of the racks through which the band is guided allowing an even spreading of the force without the necessity of a real stiff structure. Disengagement is done by losing tension and using a guiding rail to control its movement backwards. Mayor advantages compared with Bard I would be the more evenly spread forces and the possibility to use one, possibly two driving systems (e.g. cylinders or winches), instead of four at Bard I (which are used to spread the forces). It might even be possible to make use of driving systems already available on deck, when connecting the band to them.

Problems can also arise from the band itself. To be able to pull 10 MN with a wire rope the nominal diameter would be 102 mm according Vrijhof Anchors (2006, p.130) for spiral strand wire rope. This is also possible with respect to the maximum bending diameter of the rope as outlined in section 11.15.

Another problem which remains is the friction from the cable. When under tension the free run of the cable along the girder will be restrained by friction resulting in a bending moment around the guiding shoe. The problem might be overcome by tensioning when the leg is inclined away from the shoe.

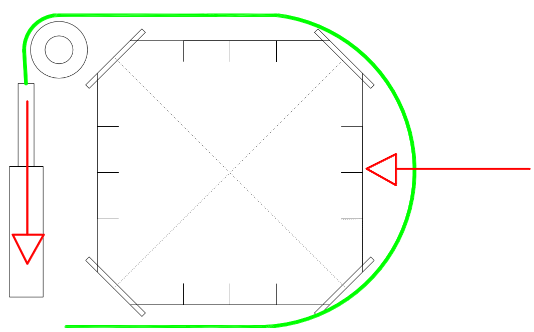


Figure 24: Band clamping 1st design

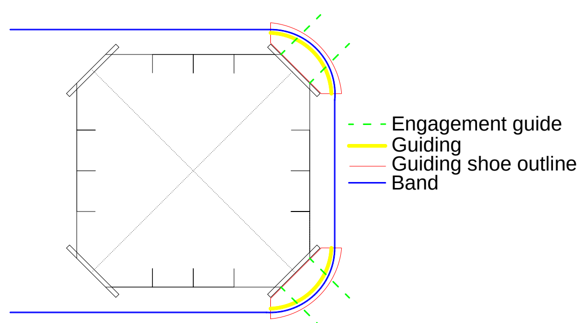



Figure 25: band clamping, global arrangement

**Description**

By making use of a band surrounding the leg running through two guide shoes placed at the racks it is possible to sea fasten the legs through tensioning this band. The tension of the band can be performed either by cylinders or winches which can be either placed in the jacking house or elsewhere. It might also be possible to make use of driving systems normally used for functions which are not needed in transit, or it might be possible interconnecting the bands of the four legs. An idea is outlined in Figure 25.

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 2 | 4 | 3 | 3 | 24 sec. | 7 | 2 |

## 4.6 LEG TRAP

The generic idea behind the leg trap was to generate an alternative to the double wedge variant. By means of taking the most feasible shape of structure in the jacking house and a special shaped part of the leg it might be possible to fasten the leg without extra driving systems but also without the extra vertical forces arising from the wedges. A possible arrangement is shown in Figure 26; the green area is the trap and the red areas are leg adjustments.

**Pitfall**
A difficulty with the leg trap would be, like the double wedge system, the placement of the adjustments to the leg, but the mayor difficulty will be the engagement of the system, because the inclinations of the leg are needed to be accounted for. The mayor advantage of this system would be that alignment of the upper system versus the lower system is not necessary. All kind of solutions, like hinges or bowl shaped catchers, are not entirely satisfactory or far more complex than the previous alternatives.

It is possible to change the leg trap system to clamp the leg by means of rotating the leg inside the jacking house when the leg is moved upwards. When wedges on the side of the rack at lower guide level contact wedges in the jacking house, the leg is turned inside the jacking house. Thereby the side of the rack at upper guide level is forced against consoles. When applying pretension the force can be delivered to the platform. Problem is the pretension needs to be at least double the amount of the tension from the environment, so the total force needs to be 20MN (over 4 consoles).This means when leaning to one side the total force in one console gets 10MN total[8]. When applying S355 with a rack width of 75mm this means a console height of at least[9] 376 mm. An idea how this works is shown in Figure 27. In this figure an upper guide section is shown. Mayor design difficulty would be to ensure all movements, rotations and displacements are aligned correctly.

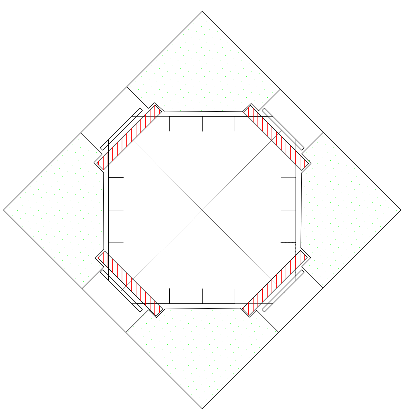


Figure 26: Leg trap

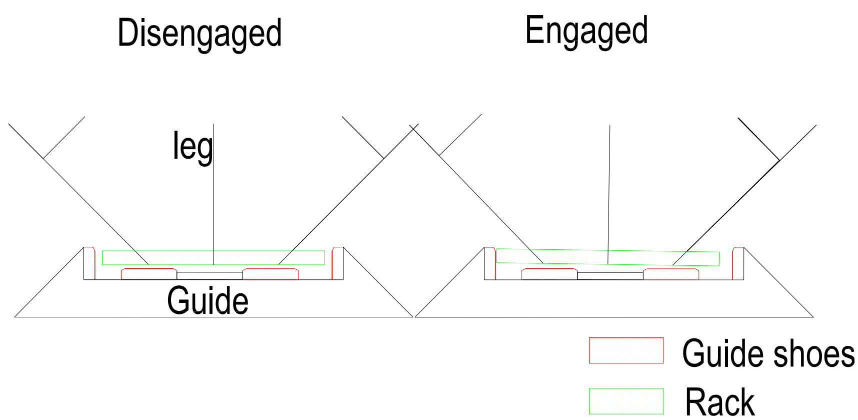


Figure 27: Leg trap detail, disengaged (I)

**Description**
When the leg is retracted the leg is turned slightly by wedge shapes around the lower guide. Through this the sides of the racks are pushed against consoles at upper guide level. By applying pretension the leg remains at those consoles when the ship swings.

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 2 | 2 | 3 | 2 | 0 sec. | 7 | 2 |

[8] $F_{total} = F_{pretension} + F_{force} = 5+5$ MN.
[9] $h_{console} = (F/\sigma_{max})/l_{rack} = (1E7/355)/75$.

## 4.7 AIR CUSHION

The final variant is the principle of air cushions to fill the gap between jacking house and the leg. The principle consists of several air cushions which inflate when the leg sea fastening system is engaged, thereby securing the leg. Major advantage is the possibility to spread the force over a large section of the leg. Major disadvantages can be the wear of the cushion, the non-even spreading of the force over the height of the cushion and the availability of the system.

**Pitfall**

According to correspondence with the company Aerofilmsystems it is possible to raise 305kN with a cushion[10] of 2.7 meters and a width of 245mm. This means with 10MN a height of about 8 meters of cushions[11]. Although implementation might be feasible, because the existence of enough space, it might still be difficult. It would be better raising pressure in the cushions. Doubling pressure would half the area needed and hence make implementation easier[12]. But cushions able to withstand this amount of pressure were not found anywhere yet.

Also when cushions are possible, a problem comes from the compressibility of air and hence the system would act like a spring. A solution can be to make use of fluids in the cushion or to make use of pancake cylinders. Pancake cylinders are flat cylinders with a large surface area. With this it would be possible to push the racks. Correspondence with Bosch-Rexroth showed a possible cylinder bore of 0.32 meters at 315bar to fasten the legs. Maximum bore which can be delivered is 1 meter. According to Bosch-Rexroth it is possible to resist rotation of the rod, possible some sort of rubber should be taken as padding to get the force straight into the leg. But it might get difficult due to inefficient cylinders and is hence thought to be less feasible.

**Description**

When the legs are fully retracted 4 pancake cylinders are activated pushing the racks towards the middle. As shown in Figure 28.

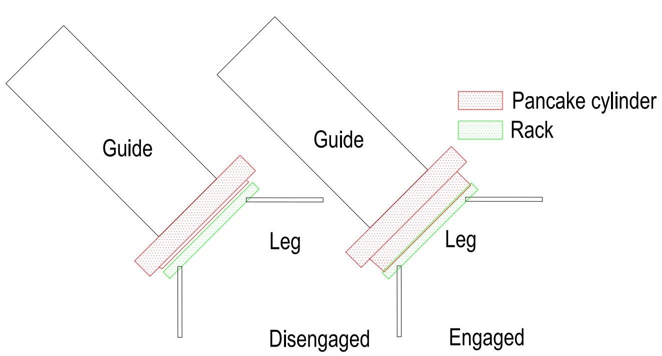



Figure 28: Air cushion detail

| Pitfall | Calc. leg | Calc. guide/ Jacking house | Calc. System | Engagement | Reliability | Ocean transit |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 3 | 56.25 sec. | 8 | 2 |

[10] With a raising height of 40mm and a pressure of 8 bars.
[11] $h_{total} = F_{total}/F_{cushion}*h_{cushion} = 10/0.3*0.245 = 8.2$
[12] With 40bar the surface needed could be 2 meters. ($A=F/\sigma$)

## 4.8 CONCLUSION

As mentioned at the beginning of this section a multi criteria analysis is conducted as a support for the decision which alternative to elaborate. Again the scores for the Bard I project are added. To enable a proper comparison the factors needed to be standardized and weighted. Standardization was done by scaling every range down to values between ten and zero where ten is the highest value. Although it seems reasonable to standardize the engagement time to the highest value accordingly, the engagement times of the systems are taken in seconds what should not be accounted for with a factor 5 in the comparison. The reason here is it is not important to win several seconds, it will be important to gain several minutes. To cope with this the comparison is taken along a time span of 10 minutes instead of the maximum value. By doing so the effect of the engagement time is somehow flattened. The results from the analysis are shown in Table 7.

The multi criteria analysis is supported by an expert meeting which was held at GustoMSC. Accordingly the choice is made to elaborate the double wedge variant.

It might be possible to use the system only on one side of the leg pushing the leg against opposite guides in order to get a three fixation point system instead of four. Three points could be more predictable and would hence be preferable. This besides that one wedge system is less expensive and would be better to align than a system with four wedges. This would mean it might be possible only to make one of the wedges adjustable for single alignment instead of alignment during every leg retraction. The second option, the leg clamp, was thought to be good but less reliable due to the large amount of (moving) parts.

| | Pitfall | Calculation leg | Calculation guide/ Jacking house | Calculation System | Engagement | Reliability | Ocean transit | Score | Rank |
|---|---|---|---|---|---|---|---|---|---|
| Bard I | 100 | 10.0 | 3.8 | 4.4 | 47.5 | 21 | 13.3 | 200.0 | n.a. |
| Rack enclosure | 100 | 10.0 | 3.8 | 3.8 | 47.5 | 18 | 13.3 | 196.3 | 5.0 |
| Wooden block variant | 100 | 10.0 | 2.5 | 2.5 | 43.3 | 27 | 13.3 | 198.6 | 3.0 |
| Double wedge | 100 | 5.0 | 3.8 | 2.5 | 50.0 | 27 | 13.3 | 201.6 | 1.0 |
| Leg clamp | 100 | 10.0 | 2.5 | 1.3 | 45.8 | 27 | 13.3 | 199.9 | 2.0 |
| Band clamping | 100 | 7.5 | 3.8 | 3.8 | 48.0 | 21 | 13.3 | 197.3 | 4.0 |
| Leg trap | 100 | 5.0 | 3.8 | 2.5 | 50.0 | 21 | 13.3 | 195.6 | 6.0 |
| Air cushion | 50 | 10.0 | 3.8 | 3.8 | 45.3 | 27 | 13.3 | 153.1 | 7.0 |
| Weight | 10 | 1 | 0.5 | 0.5 | 5 | 3 | 2 | 220 | |

Table 7: MCA elaborated principles

# 5. DETAILED ELABORATION

To get insight in the feasibility of the chosen alternative, the double wedge variant, three challenging parts of the design are further elaborated: The wedge angle, the adjustable connection and the leg changes. Before elaboration can start a more detailed force analysis should be conducted based on the DNV force analysis which was carried out before. This includes statements about the forces at the specific leg sea fastening heights, impact forces, safety factors, shear forces and rigidity. From this data it is possible to make a decision about the wedge angle. From this angle all forces in the system are available and so the adjustable connection and the leg changes can be determined. This would in the end lead to a total drawing in section 5.5.

## 5.1 FORCE ANALYSIS

### 5.1.1 Axial Forces

In section 3 a force analysis was described based on section 11.2, a detailed force analysis including the formulas used according to the DNV-regulations. From this detailed force analysis it is possible to determine the force affecting this specific chosen leg sea fastening alternative. The data can be acquired from two fixation point analysis, section 11.2.3. This is possible because when implementing the wedges in the guiding structures and hence the system acts as a two fixation point system. To prevent mayor structural changes it would be preferable to remain calculating with the system as used before: The Bard I configuration with $L_{ab,jah}$ = 54.2 m. From the leg force section it becomes clear the forces can be given according to Table 8.

| Motion | Force | Value (MN) |
| --- | --- | --- |
| Roll | $F_v$ | 4.24 |
| | $F_{hug}$ | 5.96 |
| | $F_{hlg}$ | -4.55 |
| Pitch | $F_v$ | 3.70 |
| | $F_{hug}$ | 2.98 |
| | $F_{hlg}$ | -2.26 |
| Roll/pitch (45º) $F_{roll}/\sqrt{(2)} + F_{pitch}/\sqrt{(2)}$ | $F_v$ | 5.61 |
| | $F_{hug}$ | 6.32 |
| | $F_{hlg}$ | -4.82 |

Table 8: Forces on LSFS according to DNV

The impact energy arising from the engagement of the system (when the wedges contact), is only significant if the impulse of the leg is large enough. The speed of the jacking system can be controlled up to a precision of 0.1 m/ minute or 0.0017m/s. This means the impact would be:

$$\int_{t1}^{t2} \sum F_h = m \cdot v_{h2} - m \cdot v_{h1} = m \cdot v_{h2} = l_{leg} \cdot \rho_{leg} \cdot v_{h2}$$ [13]

$$\int_{t1}^{t2} \sum F_h = 0.0017 \cdot 6500 * 71.2 = 771.3Ns$$

This is not much and hence impact should not be accounted for.

[13] $v_{h1}$ = speed before impact, $v_{h2}$ = speed after impact.

The assumption was made the guides are able to withstand the force. This means only the leg sea fastening system should be dimensioned. When referring to the global design from the elaborated principle, section 4.4, the wedges are located at the hull section of the leg. The hull section is placed facing pure roll or pure pitch motion. To get the lowest force combination in the leg fixation system it is hence preferable, referring to Table 8, to design the wedges in the pitch direction of the platform. Care should be taken when the force is directed along the surface of the wedge. Here the force will be distributed along all three fixation points through rotation. This is not further researched in this thesis.

It should again be mentioned the vertical force arisen from the environment will be transferred to the jacking system and should hence not be taken by the leg sea fastening system. The forces in the lower guides are given negative which only means a force in opposite direction; hence the upper and lower guide forces act as a couple reacting the bending moment from the cantilever section of the leg. Because the upper wedges are facing larger forces and carry the adjustable section, only these wedges are elaborated.

### 5.1.2 Safety factors:

For safe calculation of the structure it is necessary to apply safety factors to the maximum allowable stress of the used materials. A global safety factor of 1.5 should be taken in order to calculate according to Det Norske Veritas (2007, pag. 28). This factor is taken for load case 1 which would be feasible, because this is only a concept design. A safety factor should be taken into account to get a more rigid concept. With steel S355 this would result in a maximum allowable stress[14] of 236.7 N/mm$^2$.

### 5.1.3 Shear forces

When the fixation section is loaded along its surface, large shear forces can arise. Certainly with a small wedge angle this could get significant: high normal force and hence large friction forces. As usual the friction force can be derived from:

$$F_w = F_n \cdot c_w$$

$F_w$ = friction force
$F_n$ = normal force
$c_w$ = friction coefficient

For positive friction or smooth and lubricated steel the friction coefficient should be taken as 0.1. For negative friction or rough and dirty steel the friction coefficient should be taken as 0.5.

### 5.1.4 Rigidity

Although most preferable design situation would be to have zero margins when engaged, this would not be feasible. Used materials will deform, certainly with these large forces, and wear would also occur. Because of this it is necessary to establish a feasible margin to the system.

The maximum available spacing to overcome with the fastening system (guide-leg-guide) would be between 20 and 30mm between two opposite guides for the Bard I system. The main purpose of the fixation system is to prevent the leg from hitting the sides and from creating disturbing noises and vibrations. So a distance[15] of 5mm per side should be overcome at least with

[14] $\sigma_{allowable} = \sigma_{max} / \gamma = 355/1.5\ N/mm^2$
[15] $L_{adjust} = (L_{gapmax} - L_{gapmin})/2 = (30-20)/2\ m$ = Maximum wear of the guide shoes.

adjustable alignment at a total of 30mm.

The wedges may overcome the spacing of 30mm but it would not solve deformation. Hence it would be necessary to stiffen the legs at fixation level to obtain enough deformation stiffness at the leg hull when the leg leans towards the wedges or the guides. It is also necessary to design the jacking house acting almost infinitely stiff, and hence pulling the opposite guides towards the leg. In practice this is assumed to be a limit of 2.7 mm displacement[16] of the wedge connected section, which is almost infinitely over these dimensions.

This would imply a maximum of 9.5MN when making use of a 2800mm long HE1000M beam, with the design info gathered from www.constructalia.com and a mechanical system as outlined in Figure 29, behind the wedge system of 1000 mm width[17]. So the maximum allowable force will be 6.3MN when the safety factor is taken into account[18].

The shrinking of the leg should stay under[19] 4mm to prevent from too much spacing and hence the necessity to over dimension the wedge system. This does not mean the deformation of leg sections should stay within these limits. Total deformation margin would than stay within 6.7 mm.

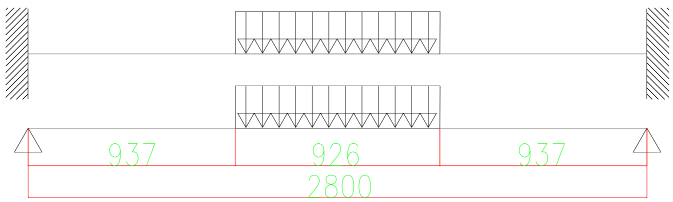



Figure 29: Detail design, mechanical drawings

## 5.2 WEDGE DESIGN

For the design of the wedges several factors play a role:

- Dimension limitations.
- Force distribution through legs and jacking house/ guiding structure
- Disengagement force (and hence angle of the legs). With respect to strength of the jacking house structure.

### 5.2.1 Dimension limitations.

When assuming the wedges to be made of S355 this would imply a minimum contact area A and a minimum sliding area with a length of *s* when taking a fastening gap *d* of 20mm.

$$A = \frac{F_{n2max}}{\frac{355\ N/mm^2}{1.5}}$$

$$s = \frac{d}{\sin(\alpha)} = \frac{20}{\sin(\alpha)}$$

[16] 0.1% of the total leg hull length.
[17] Maximum available wedge width.
[18] $F_{3max} = F_{max}/\gamma = 9.5/1.5\ MN$ = maximum normal force through leg divided by safety factor.
[19] 0.1% of the total width of the leg.

The available width in the jacking house beside the leg hull is around 2600 mm, when calculating with a supporting structure of HE1000M this would leave 1600 mm of space, so there is enough space for wedges.

### 5.2.2 Force distribution

Before calculation can begin it has to be mentioned it is necessary to evaluate certain load cases. This has to be done because a static system will act different than a dynamic system and also disengagement would cause different forces in the system, e.g. friction would be negative instead of positive with engagement. The necessary load cases are:

- Engagement with leg force
- Engagement with reversed leg force
- Static with leg force
- Static with reversed leg force
- Disengagement with leg force
- Disengagement with reversed leg force

Calculation of the forces in engaging situation is done with respect to Figure 30 combined with the basics of horizontal and vertical equilibriums. For the static load case the middle friction force ($F_{w2}$) can be removed, because this force does not apply in static situation.

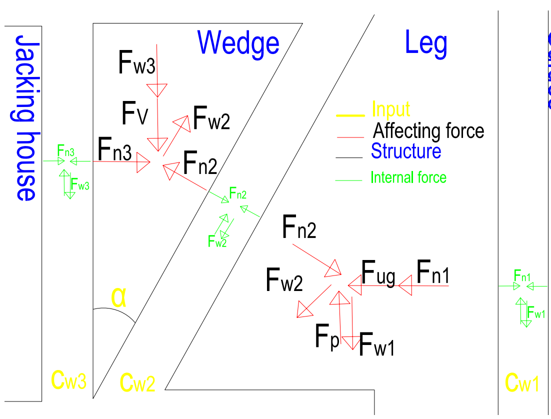



Figure 30: Force distribution engaging

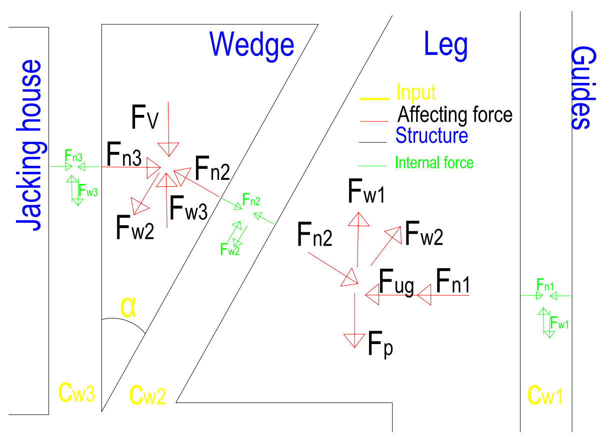



Figure 31: Force distribution disengaging

Calculation of the forces for disengagement can be done according to Figure 31. Care has to be taken here because two disengagement options are available. It is possible the wedge breaks loose from the leg, which is required, but it is also possible the wedge combined with the leg breaks loose from the jacking house. This means the conduction of two calculations, one with the force equilibrium of only the wedge to determine the force needed to get the leg off the wedge and one calculation with the system where wedge and leg are combined into one element to determine the extra force needed upward to prevent the wedge from going down.
For calculation the assumption is made $F_{n1}$ is zero because it will be small and without knowing the actual size of this force it is not possible to perform the calculation.

| | |
|---|---|
| $c_{w1}$ | Friction coefficient: guide – leg |
| $c_{w2}$ | Friction coefficient: wedge – leg |
| $c_{w3}$ | Friction coefficient: wedge – jacking house |
| $F_{fug}$ | Environmental force |
| $F_{n1}$ | Normal force: guide – leg |
| $F_{n2}$ | Normal force: wedge – leg |
| $F_{n3}$ | Normal force: wedge – jacking house |

| | |
|---|---|
| $F_p$ | Pretension/ pull out force |
| $F_v$ | Vertical force wedge |
| $F_{w1}$ | Friction force: guide – leg |
| $F_{w2}$ | Friction force: wedge – leg |
| $F_{w3}$ | Friction force: wedge – jacking house |
| $\alpha$ | Wedge angle |

Table 9: Signs of force distribution engaging

For the necessary space inside the jacking house it is preferable to get an angle as small as possible. The friction coefficients are taken as 0.1 for smooth steel and 0.5 for damaged steel whenever they make the angle larger (and so the calculation would be conservative). The pretension force used can be calculated as the necessary force to prevent the leg from sliding down by cause of $F_{ug}$ or the force necessary to slide the leg up and can be calculated according to Figure 32. The pretension needs to be multiplied by 10% because of tension loss due to cooling of the hydraulic oil. Horizontal and vertical equilibrium should be reached according to:

$$\sum F_h = -F_{ug} + \cos(\alpha) * F_{n2} - \sin(\alpha) * F_{w2}$$

$$\sum F_v = F_p - \cos(\alpha) * F_{w2} - \sin(\alpha) * F_{n2}$$

$$F_p = \frac{F_{ug} * [\cos(\alpha) * c_{w2} + \sin(\alpha)]}{\cos(\alpha) - \sin(\alpha) * c_{w2}}$$

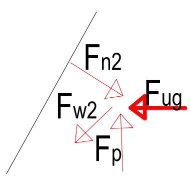



Figure 32: Pretension calculation

### 5.2.3 Decision of the wedge angle

From the mechanical model created in the previous section the arising forces were calculated for every load case with several wedge angles according to the formulas mentioned in section 11.17. The angle of the wedge needs to be as small as possible because it would ease the pull in. The decision which angle to take was made on the following criteria:

- Maximum force $F_{n3}$ due to bending of the Jacking house: 6.3MN.
- All angles above the self loosening angle are larger than necessary.
- The angle with the smallest $F_v$ in positive or negative direction should be taken because this would cause the adjustable connection to be as less loaded as possible.

From this the angle to take will be: 7 degrees when the wedges are lubricated during the pull in. All important values for all load cases which are connected with this wedge angle are given in Table 10. The pretension force is the extra force needed from the jacking system besides the forces needed to haul up the leg.

Interesting are all the zero numbers. Due to lack of contact between leg and guide when the leg leans away from the guides, there will be no forces in the wedges. The zero vertical force in static situation means there is no support force needed during equilibrium, due to friction. During pull with environmental forces away from the wedge, there will be little to no force through the wedges.

The friction coefficients used are given in the second part of Table 10. The coefficients are based on worst cases, except from $c_{w2}$ during pull in. This coefficient is taken 0.2 because it is possible lubricating the wedge before haul up. The second friction coefficient is left out in static situation because this one should not be overcome, in order to reach equilibrium.

| Situation | Description | Symbol | $F_{ug}$ = +3 MN | $F_{ug}$ = -3 MN | unit |
|---|---|---|---|---|---|
| | Angle | $\alpha$ | 7.00 | 7.00 | Degree |
| | Pretension | $F_p$ | 1.09 | 1.09 | MN |
| Drive in | Normal | $F_{n2}$ | 3.22 | 0.00 | MN |
| | Vertical | $F_v$ | 0.72 | 0.00 | MN |
| | Normal | $F_{n1}$ | 0.12 | 3.00 | MN |
| | Normal | $F_{n3}$ | 3.12 | 0.00 | MN |
| Static | Normal | $F_{n2}$ | 4.75 | 0.46 | MN |
| | Vertical | $F_v$ | 0.00 | 0.00 | MN |
| | Normal | $F_{n1}$ | 1.71 | 3.45 | MN |
| | Normal | $F_{n3}$ | 4.71 | 0.45 | MN |
| Pull out | Pull out | $F_p$ | 1.07 | 1.50 | MN |
| | Support | $F_v$ | -0.77 | 0.00 | MN |

| | in | static | out |
|---|---|---|---|
| $F_{ug}$ | 3 | 3 | 3 |
| $c_{w1}$ | 0.5 | 0.3 | 0.5 |
| $c_{w2}$ | 0.2 | 0 | 0.5 |
| $c_{w3}$ | 0.1 | 0.3 | 0.1 |

Table 10: Forces and friction coefficients elaborated wedge angle

### 5.2.4 Wedge design

From out the given forces and the given angle of the wedge some basics of the wedge design can be given. When assuming the wedge to have the maximum possible width it would be 1 meter wide. Due to the formula given before the minimum extra length of the wedge and the necessary contact area has to be:

$$s = \frac{d}{\sin(\alpha)} = \frac{20}{\sin(7)} = 164mm$$

$$w = \frac{A}{l} = \frac{\frac{F_{n2}}{\sigma max}}{l} = \frac{\frac{F_{n2}}{\frac{\sigma_{355}}{\gamma}}}{l} = \left(\frac{4.19E6}{\frac{355}{1.5}}\right)/1000 = 17.7mm$$

Total height would be 181.7mm. For safety this means the wedges should have a contact area of 200mm or bigger. When made of solid steel this would mean per wedge a mass of:

$$0.5 * l * b * w * \rho_s = (0.5 * 0.024 * 0.199 * 1.0) * 7850 = 18.7kg$$

This means a total weight of the wedges of 75kg, when taking 4 pieces.

## 5.3 ADJUSTABLE CONNECTION

*From the previous section the existing forces in the system are known. From this it is possible to design the adjustable connection. This connection between wedge and jacking house, see also section 5.5, is necessary to overcome the difference of at most 10mm from wear, which would mean an adjustment height of a maximum of* $\frac{10}{tan\,(\alpha)}$. *This would with a seven degree angle mean an adjustable height of 81mm. Several options are elaborated to establish some key elements and to establish key configurations of these alternatives. These options are compared to their advantages and disadvantages.*

### 5.3.1 Pretension bolts

It is possible to overcome the distance and vertical forces by increasing the friction between the wedge and the jacking house, by increasing the friction coefficient and/ or increasing the normal force in this plain. This last option is possible when using a pretension connection. The necessary pretension can be given as a combination of the maximum necessary vertical support force with a friction coefficient.

$$F_{bolt} = F_{vmax}/c_{w3} = 0.77E6/c_{w3}$$

Maximum pretension which is possible will be 236.7 N/mm$^2$, referring to the maximum stress in steel, as already made clear in section 5.1.2. Because adjustment of the distance is obligatory sliding holes should be applied which would mean less than the area of the bolts head and of the nut could be used for pretension. Solution is to use a connection plate between the sliding holes and the bolt heads.
For the double wedge this would lead to 110 pieces of M20 bolts with quality 8.8, referring to 11.18, which would be unfeasible to adjust and also would these bolts be hard to reach in this arrangement.

### 5.3.2 Bolt spacers

Besides using friction to overcome the vertical force combined with adjustment, it is possible to create an impact surface where against the wedge slides. When designing the impact surface to be adjustable with respect to the mounting all demands are full filled. The adjustment could be done by using bolts set at a given distance. This means the bolt needs free rotation at the impact surface. How this works is illustrated in Figure 33.
The amount of bolts needed could be determined according to the strength of the weakest link during axial loading: The thread of the bolts. When referring to www.tribologie.nl the maximum strength of a M20 bolt (quality 8.8) thread would be 195.8 kN[20]. The amount of bolts would be:

$$n_{bolts} = \frac{F_{vpos}}{\left(\frac{F_{boltspacer}}{\gamma}\right)} = \frac{0.72E6}{\frac{195.8E3}{1.5}} = 6pcs$$

Advantages:

- Possibly cheap.
- Far better and faster to reach and adjust than the pretension bolts.

[20] Width tread length *of 0.75*D = 15mm*

Disadvantages

- Not self adjustable, but if wear does not occur too fast it might be feasible.
- It might be difficult to get the bolts at the same height.
- Special device needed for disengagement, some console where the wedge disconnects to.

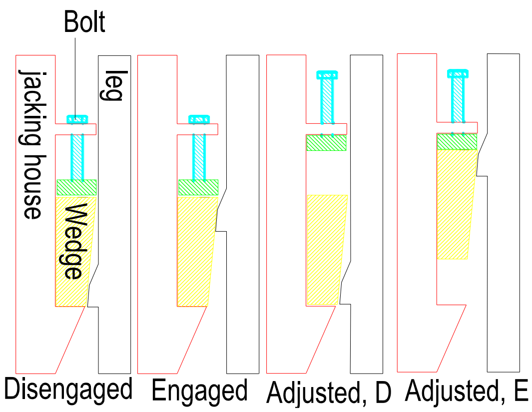


Figure 33: Bolt spacers working principle

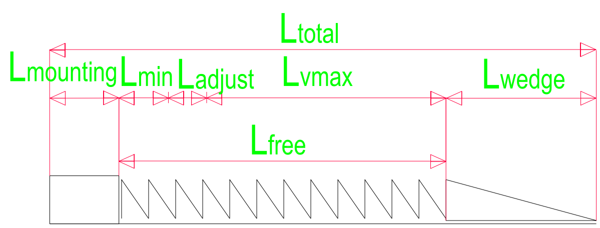


Figure 34: Spring dimensions

### 5.3.3 Top spring

When applying a spring at the top of the wedge which is able to generate a force equal to the maximum vertical force at a certain impressed length combined with the extra force generated by the impression of the spring due to the vertical adjustment, it might be possible to get a self adjustable connection. Care has to be taken the extra force due to the adjustment stays within acceptable limits because it would mean an increase in the necessary pretension.
The spring force can be given as the spring constant multiplied by the impress of the spring:

$$F_{spring} = k_t * \Delta x$$

In order to reduce the extra force exerting from the adjustable connection the extra impression should be relatively small. This extra impression would be a maximum of 81 mm, the adjustable height. It is possible to assume the wear of the guiding shoes to be relatively small. Hence it is possible designing the spring only for a smaller travelling distance of the spring.

In Figure 34 the main dimensions of the spring system are given[21]. $L_{free}$ is the free length of the spring, or the length of the spring without tension. $L_{min}$ is the minimal length of the spring, or the amount of coils times the wire thickness. $L_{adjust}$ is the adjustable length. $L_{vmax}$ is the length where the maximum vertical force should be reached.

When assuming the total system to be placed within the guiding system $L_{total}$ has a maximum of 1000mm. When no pretension is considered and when the mounting height is assumed to be the same as the wedge height (200mm), the free length will be:

$$L_{free} = L_{total} - L_{wedge} - L_{mounting} = 1000 - 200 - 200 = 600mm$$

[21] The figure is turned over 90 degrees.

For calculation of the necessary spring specifications for rough work it was possible to make use of the helical spring calculator from www.tribolotie-abc.com. Input here is a force of 800kN in total[22]. When also the rules set by www.spring-makers-resource.net are applied to get a minimum index (*D/d*) of 4 and a minimum pitch angle of 10 degrees, it is possible to establish a feasible spring. When making use of 3 springs with 300mm diameter and 75mm wire, it is possible to get a spring stiffness of 1290kN/m. With 40mm this means a force increase of:

$$F_{spring} = k_t * \Delta x = 1290 * 0.04 = 52 \text{ kN}$$

This is below the 10% extra force which had been taken before. The characteristics of this spring can be found in section 0.

However, the spreading of the load through the spring needs to be as centralized as possible to prevent from buckling. This would be possible when the wedge is prevented from rotation. This would result in a wedge as shown in Figure 35. It is shown the impact area of the wedge is moved further into the jacking house in order to centralize the load. The springs on top of the wedges are in this way evenly loaded; still the wedge needs to be supported at the leg side of the jacking house to be sure no buckling arises.

Advantages:

- Self adjustable.

Disadvantages:

- Availability of the spring and the costs of such a spring.
- Little overcapacity, spring is limiting factor.

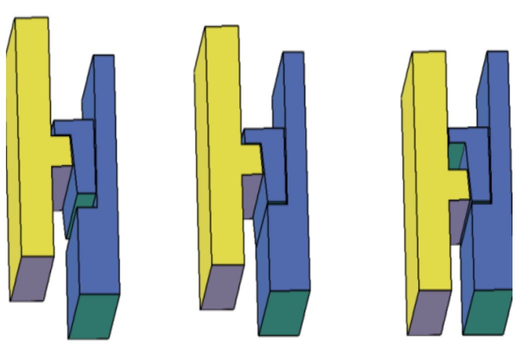


Figure 35: Top spring configuration, yellow = jacking house, blue = leg + wedge; engaged (l = adjusted, m = not adjusted), disengaged (r)

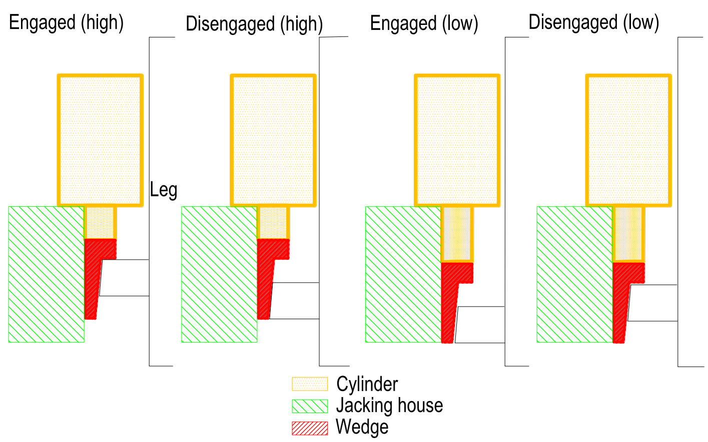



Figure 36: Cylinder mounting: eng. (l), dis (lm), dis. with stroke (rm), eng with stroke (r)

[22] $F_{spring} \approx F_{vmax} * 1.1$ MN

### 5.3.4 Cylinder mounting

Instead of a spring it would also be possible to use hydraulic cylinders. This mean the connection height can be changed by adjusting the pressure.

Although this alternative requires an active system to compensate wear of the guiding shoes, which is in contradictory compared with the principle of the system, it might have some advantages. The total force which was necessary to generate with the Bard I system will be smaller, because the bulk of the force is distributed through the jacking house instead of the driving system. Only a single acting plunger with a 200 mm piston would be able to generate 1MN which would be enough with the cylinder mounting. The total size of this cylinder including an 80mm stroke would be: 628mm. When not making use of wedge lubrication it might be necessary to use cylinders able to apply 1.8MN[23] in order to overcome total friction to pull the leg aside (which would be 60% of the force of Bard I). It might be possible to use several smaller cylinders with less pressure in order to reduce the size of the cylinders. It would still be necessary to have a console for the pull out (or double acting cylinders should be taken). The arrangement is shown in .

The system now more or less acts like the wooden block variant as was mentioned earlier in section 4.2. Question remains if this system is more feasible than previous leg sea fastening systems. Although the necessary cylinder power is less, extra consoles are needs, the leg has to stiffened and the upper guide is not just horizontal loaded but with this system also vertical.

Advantages:

- Hydraulic adjustable.
- No force building due to misalignment.

Disadvantages:

- Again cylinders needed, though less powerful than Bard I, the system requires more other elements to ensure total leg sea fastening.

### 5.3.5 Conclusion adjustable connection

Though several options are available, every option has its advantages and disadvantages. In order to remain feasible it is necessary to establish the most promising option. From the experience of GustoMSC with the Mayflower Resolution system the wear will be very little over a large period, approximately 10mm in about 10 years. So hand wise adjustments can be made.

The extra normal forces necessary with the pretension bolt system is not feasible to reach and would hence make the double wedge system far from preferable.

The bolt spacer option would be more feasible due to only 10% or less bolts needed than with the pretension variant. However this system would not be self adjustable. When too much wear exists the leg would get the opportunity to rotate through the guiding shoes and the wedge enabling it to generate even more wear. This means the adjustments are to be made regarding to this wear. However this is expected to be little so deformations can be compensated by hand.

The top spring would be self adjustable; however it could be very expensive because of the expensive spring. Also the design gets more difficult when the vertical forces are building, e.g. when designing for ocean transit conditions.

[23] $F_{cyl,unlybricated} = F_{ug}*(c_{w2}+c_{w3}) = 3*(0.5+0.1)\ MN$

Cylinder mounting would be feasible because adjustments can be made anytime, even when the leg is already fully retracted. However due to the extra necessary elements and still the necessary hydraulic cylinders question remains if it would not be better to push from aside with some stronger cylinders like the Bard I system, also from a cost effective view.

Concluded, due to wear and the costs expected for every option, the bolt spacer variant would be most feasible. Mass of this variant will be 67kg, according to section 11.20.

## 5.4 LEG CHANGES

*Due to the large normal forces acting through the leg it would be necessary to have a closer look at the leg section where the wedge connects to, see again section 5.5. The hull side of the leg is relatively weak hence it would certainly not be able withstand the normal forces. To gain insight in the necessary adjustments a preposition is made in order to establish the necessary amount of changes.*

### 5.4.1 Force analysis

The force affecting the leg section would be $F_{n2}$ of 4.19 MN acting at seven degrees. This force acts on a surface of 1000*40mm. This load is assumed to be acting continuous on 1000mm.

Besides the normal loads, the vertical load ($F_p$) needs to be transported to the wedge, but the hull is assumed to be large enough to carry this, as long as the hull is not too far bended by the normal forces at the wedges location.

### 5.4.2 Hull Stiffeners

The easiest way to stiffen the legs is by applying stiffeners to the wedge connected hull side, generating a larger moment of inertia to the hull of the leg.

When determining the maximum bending situation for the first calculation for the leg hull stiffener it needs to be assumed to be hinged at both sides. With a maximum bending of 4mm this means a minimum moment of inertia of 2.14E9 $mm^4$ (corresponding to HE700A). A stiffener as HE700A could be applied with the given moment of inertia, but because the stiffener is only loaded by bending it would be better applying IPE750x169 (saving 8kg/m). The moment of inertia of this rolled beam is 2.4E9 $mm^4$. The weight of this profile is 196kg/m.

When maximum bending moments are calculated for the rack-hull-connection with fixed connections at both sides, maximum bending moments with the given moment of inertia would be 1.39E3 kNm. This means the non wedge hull should be able to carry this bending moment. When they also are assumed to be hinged, an extra stiffener with a moment of inertia of 8.7E8$mm^4$ should be enough to remain within 4mm bending, which corresponds to a HE500A (axial loaded). The total displacement of this stiffener framework should also be checked.

The total leg displacement of 4mm counts for the whole leg. For this reason the total framework of stiffeners was checked for the displacement. For this quick calculation the program Framework2D was used. For the lengths the c-c distance were taken.

It became quite clear the displacement of the leg hull section of 8mm came beneath the wedge which is far beyond 4mm with the given profiles. For this reason it is necessary to use a HE1000M instead of an IPE750x169. The reason here is the system used in the previous section had non displaceable nodes, but those connections can displace in the total system because they lean away from the guides. The in and output of the computer program are given in section 11.24. Corresponding input figure and the M-S-N-lines (bending moment, shear force and normal force) are given in section 11.22.

The total stiffener configuration is shown in Figure 37. Total mass of these stiffeners would be 1845kg[24].

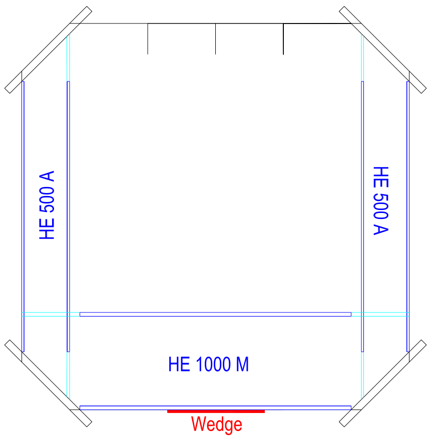



Figure 37: Hull stiffener configuration

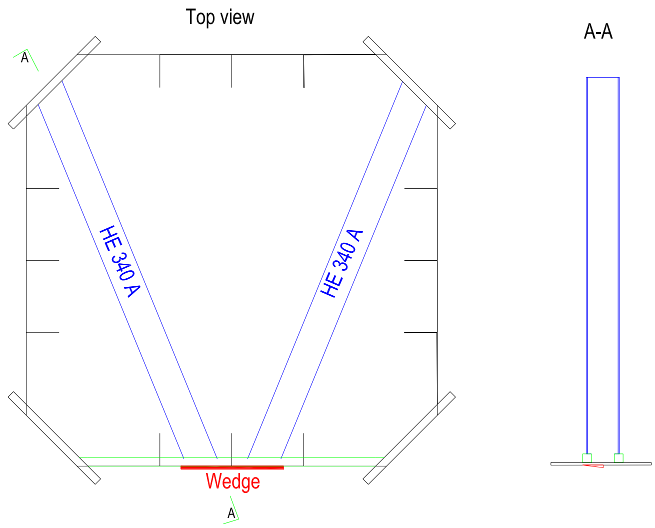



Figure 38: Triangle stiffener configuration

### 5.4.3 Triangle stiffening

Another option is to make use of a triangle connection between the wedge and the two opposite guides. It might be possible here to make use of lighter profiles. The stiffeners which could be used are HE 340 A, according to calculations with Framework 2D with a mass of 882kg[25], all input and output data including M-S-N-lines can be found in sections 11.23 and 11.24.

The arising problem here would be the connection leg hull/ wedge/ stiffeners. Due to the weight of the stiffeners a bending moment of 10.6kNm[26] in the leg hull will arise combined with a shear force of 4.4kN[27]. This will be distributed along the 330mm stiffener height, resulting in 32.1kN reaction forces. When these are assumed to be point loads on a fixated beam the dimensions of a square connection bar with the moment of inertia needs to be:

$$I = (F * l^3)/(\omega * 192 * E) = (32100 * (2800)^3)/(4 * 192 * 2.1E5) = 4.4E6mm^4$$

$$I = (b * h^3)/12 = d^4/12 \rightarrow d = \sqrt[4]{(12 * I)} = \sqrt[4]{(12 * 4.4E6)} = 85mm$$

All this combined would result in Figure 38. The total stiffener mass than becomes 1200kg[28].

### 5.4.4 Conclusion

Due to less mass in the triangle stiffening option, the leg stays lighter and also the necessary connections are less. From a cost effective point of view it is preferable to have less connections and material use. For this reason it might be preferable to use the triangle stiffening alternative.

---

24 $L_{leghull}*\rho_{HE1000M}+2x\ L_{leghull}*\rho_{HE500A} = 2.8*349+2*2.8*155$
25 $m_{diagnoal} = 2*L_{diagonal}*\rho_{HE340A} = (2*4.2*105)$
26 $M_{triangle} = 2*g*\ \rho_{HE340A}*\ L_{diagonal}*(0.5*\ L_{diagonal}) = (2*10*105*4.2*1.2)$
27 $d_{triangle} = 2*g*L_{diagonal}*\rho_{HE340A}/2 = 2*10*4.2*105/2$
28 $m_{triangle} = m_{diagnoal}+2*d^2*l_{connector}*\rho_{steel} = 882+2*\ 0.085^2*2.8*7850.$

## 5.5 FINAL DRAWING

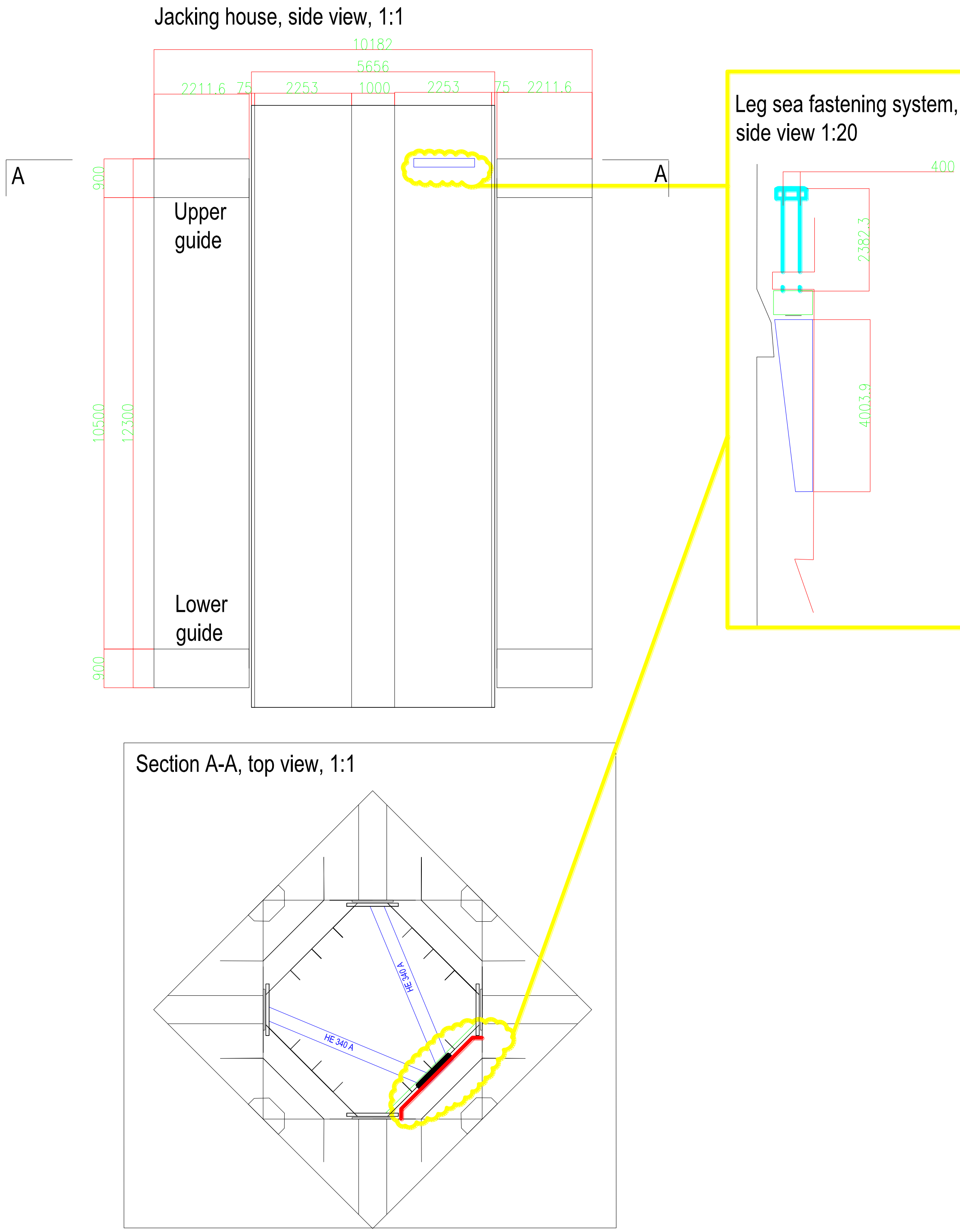



Figure 39: Final drawing double wedge system

# 6. COMPARISON

*This thesis was initiated because a creative alternative to the Bard I leg sea fastening system needed to be designed. By establishing the design features and behavior it becomes possible to compare the design with the Bard I leg sea fastening system. By this conclusions can be drawn about the usability and feasibility of the chosen design. The establishment and comparison is done according to the GustoMSC demands as set in section 1. The demand was to improve the following aspects: Costs, safety, reliability, engagement time, engagement costs and calculation time. Also some remarks are made about the possibility to adapt the design to ocean transit conditions as mentioned in section 3.2.*

Establishing the *costs* of the double wedge system with today's turbulent steel prices would be without practical use. It would however be more useful only mentioning the mass of the systems involved. The double wedge system has a total weight of about 1342kg[29].

Because the leg is hold upward by the jacking system great *safety* hazards will not occur as a result of the proposed leg sea fastening system. But great care has to be taken to prevent the system from being overloaded. Mayor damage can be brought to the leg and guiding structure when overloading occurs. It would probably be necessary to apply some sort of monitoring to reduce this risk because the jacking system is able to generate far more force than the necessary pretension.

Remarks about the *reliability* of the system are exerting from the amount of moving parts involved in the sea fastening system and all the margins and deformations which were used or can exert during the lifetime of the system.
Margins and deformations gathered from section 5.1.

- Leg deformation: max: 4.0 mm.
- Jacking house deformation: max: 2.7 mm.
- Fastening gap: min: 20.0 mm, max: 30.0 mm.
- Wear and tear: max: 10.0 mm.
- Adjustable height: max: 80.0 mm.

This means when disengaged the leg has the ability to move in a space between 20 and 30mm, when engaged the possible movement is exerting from the deformations which will be 2.7mm to one side and 4mm to the other side, a total of 6.7mm. When the adjustable connection is not set properly this will increase.

*Engagement* is done by retracting the leg against the wedges. This only means the speed during contact needs to be controlled very accurate to prevent from too heavy impact and overloading. Also no extra people need to be involved. Once in a while the adjustable connection needs to be adjusted in order to reduce the remaining fastening gap.

*Calculation time* which is extra needed for double wedge mostly consist of determining the optimal angle for which a basis has been given in this document. Primary objectives are to

[29] Total mass = f*our wedges (4*18.7=75kg) + bolt spacer (67kg) + triangle stiffening (1200kg).*

reduce the forces in the adjustable connection and to reduce the size of the leg changes, which count for around 90% of the systems weight.

Designing the system for *ocean transit* conditions would of course increase all the forces and structures involved. However the leg stiffening structures weight should be watched closely, because it is the heaviest part of the leg sea fastening system and its weight would increase accordingly. This might affect the capabilities of the jacking system too much.

When making use of the data in section 2.3, where the Bard I system was shortly described, it is possible to compare the double wedge system with Bard I. The principle of both systems is equal: pushing the leg to one side. But because double wedge is a passive system the engagement time will be less. Just hauling up the leg is enough for fixation. Just like the Bard I system the LSFS only works when the leg is fully retracted. Difference would be the Bard I system uses expensive cylinders and the double wedge system needs heavy leg adjustments. The leg structure under research for the stiffening was purely based on the non-bulkhead sections of the leg. Still at some heights there is need for bulkhead sections so it might be possible combining these sections further reducing the extra weight.
Deformation exerting from loads would always remain but the main advantage of the Bard I system over the double wedge variant will be the active engagement. This is positive because adjustment for wear and tear can be made every engagement. However wear is assumed not to be too much to overcome by the adjustable connection of the upper wedge as proposed. Advantage of the double wedge variant over Bard I would be it is passive and would not need extra controlling and energy.

All concluded it was demanded the system should as far as possible improve costs, safety, reliability, engagement time, engagement costs and calculation time.

- When costs will be referred to as weight the double wedge system might improve this (+).
- Both systems would not cause great safety hazards (+/-).
- Reliability might improve because there are no moving parts. However the loads should be monitored more closely to prevent from overloading. (+/-).
- Engagement time and costs are reduced because the system is passive (+).
- Calculation time however will increase because extra stiffening of the leg is necessary and the calculation of the wedges would be more difficult than the calculation of the sea fastening jacks used on Bard I (-).

The systems complexity of the sea fastening system would increase when choosing the double wedge system in exchange of faster and cheaper engagement.

# 7. DISCUSSION

*Though this thesis was conducted with great care still some uncertainties remain. For a part these arise from the boundaries set by the thesis span and some assumptions which were made with as much care as possible. However before it is possible to use the proposed leg sea fastening system some extra research should be carried out. Besides this some aspects need to be pointed out for detailed reconsideration.*

All values in this thesis are used as a guiding for the design, this values could and should change when the proposed alternative, double wedge, is used for a particular platform.

For applied design more load combinations to the system should be investigated, especially for the establishment of the wedge angle. It is also advisable to have a closer look at the needed safety coefficients simultaneously. Loading under an angle with respect to the wedges should be investigated also.

The adjustable connection should be further investigated, especially the two plates where the bolts run through: The top one which carry the thread and the lower plate which will carry the impact from the wedge.

To be sure the guiding structure is able to carry the loads exerting from the double wedge system it should be necessary to apply the loads of the double wedge system in a finite element analysis of the guiding structure. By this it is possible to figure out what effect the leg sea fastening system will have on the guiding structure and jacking house configuration. Especially the exerting vertical forces combined with the guiding structure could carry some problems. Also the assumption of the HE 1000 M beam as a connection for the wedges should be reconsidered in this analysis.

For the leg stiffening it would be necessary to apply several load cases, more over because of ocean transit conditions which were not further discussed in this thesis. Extra precautions to be able to carry the loads from the ocean transit conditions should be made to prevent the leg hull from carrying too much load or to design the leg stiffening with respect to this load. It should also be considered combining the stiffening with for instance the bulkhead sections of the leg to reduce additional weight.

Also it would be necessary having a closer look to the impact of losing one of four holes available for exchanging jacking system parts as described in section 11.7. However it is assumed to be no great problem.

Besides the statements above, this document provides a good outline about the problem and a wide span of the possible solutions. The elaborated design provides a solid foundation for further design and the given calculations span a great deal of the problems, loads and construction parts involved.

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# 9. TABLE OF FIGURES

# 10. TABLE OF TABLES

# 11. ATTACHMENTS

## 11.1 CONTENTS

## 11.2 FORCE ANALYSIS

*In order to develop a new leg sea fastening system it is important to gain insight in the forces affecting the legs under tow. The general derivation of the forces can be done according Det Norske Veritas regulations combined with the rules set by Germanischer Lloyds. The force analysis is split in three stages: general force analysis to establish the forces at the legs, a two fixation point analysis and a three fixation point analysis, to determine the effects when making use of those arrangements. The forces are calculated for ocean transit conditions and field transit conditions combined with roll and pitch motions.*

### 11.2.1 Field and Ocean transit

For the forces in the leg sea fastening system a difference has to be made according to the difference between "field transit" and "ocean transit". Germanischer Lloyd gives some input for this difference.

For field transit conditions Gl-group (2008) cited:
"*Legs are to be designed for a bending moment resulting from a 6° single amplitude of roll or pitch at the natural period of the unit, plus 120 % of the gravity moment caused by the legs' angle of inclination."*
For ocean transit conditions Gl-group (2008) cited:
"*Legs shall be designed for acceleration and gravity moments resulting from the motions in the most severe anticipated environmental transit conditions, together with corresponding wind moments. Calculation or model test methods, acceptable to GL, may be used. Alternatively, legs may be designed for a bending moment resulting from a 15° single amplitude of roll or pitch at a 10 second period, plus 120 % of the gravity moment caused by the legs' angle of inclination (minimum design criteria)"*

### 11.2.2 DNV calculations

The loads on the leg sea fastening system are determined according to the calculation proposed by Det Norske Veritas (DNV). Most important statements are mentioned here as also the outcomes of the analysis. Further description about the calculations can be found in section 11.3 and 11.4.
As cited in Det Norske Veritas (1992, par. 5.3.2):
*"In general the legs are to be designed for static forces and inertia forces resulting from the motions in the most severe environmental transit conditions, combined with wind forces resulting from the maximum wind velocity. Wave motions may be obtained either from model tests or from computations."*
As cited in Det Norske Vertitas (1992, par. 5.3.3):
*"In lieu of more accurate analysis it is possible to resort to a simplified analysis procedure described in the Rules. According to this procedure it is sufficient to consider the following loads:*

- Inertia forces corresponding to a specified amplitude of roll or pitch motion at the natural period of the platform.
- Static forces corresponding to the maximum inclination to the legs due to rolling or pitching
- Wind forces corresponding to a specified wind velocity

*The effect of heave, surge and sway are implicitly accounted for by use of a specified load factor, γ = 1.2."*

For use in this thesis it is suitable to use only the simplified calculation method. Reason here is that the sea fastening system is not designed especially for a ship, so rough calculation of the existing forces are enough.

Input necessary for the DNV-calculations was gathered from the Bard I project:

- Leg length (71200 mm)
- Distance between guides (13180 mm c-c)
- Mass of the leg (taken equal over the length of the leg: 6700 kg/m)
- Bending resistance of the legs (according to attachment 11.5)
- Distance between still water level and the lower guide (1500 mm c-c)

### 11.2.3 Two fixation points

To evaluate the forces corresponding to the system with one hinge and one roller, the horizontal forces were calculated for each $l_{ab,gu}$[30] between 64.1 m and 39.1 m with a step size of 0.1 meter. The forces for the lower and upper guides are calculated with use of the following formulas containing $F_{hu}$ as the horizontal force in the upper guide and $F_{hl}$ as the horizontal force in the lower guide as a result of $M_0$ calculated from DNV formulas:

$$F_{hu} = F_0 + F_{hl}$$
$$F_{hl} = -M_0/(l_{ab,swl} + l_{bet,lgu-swl})$$

The results are given in Figure 40. The figure shows the force versus different heights of the legs in field roll conditions.

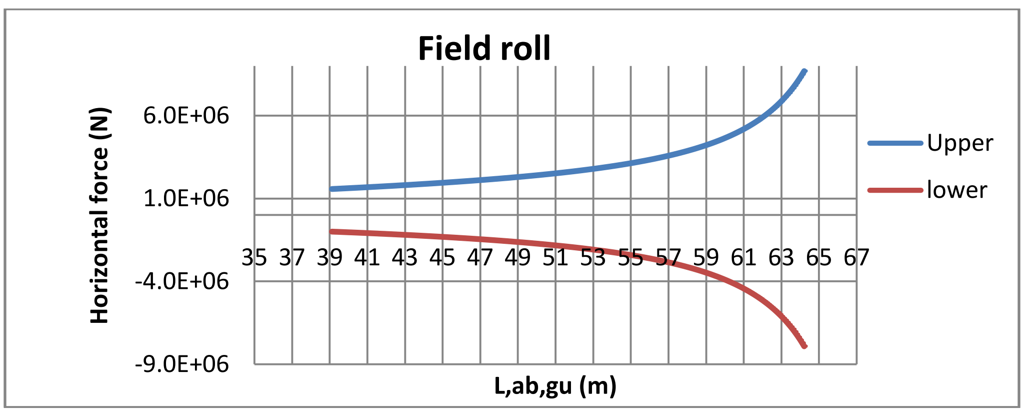


Figure 40: Two fixation point analysis: Field Roll

An analysis has been conducted to establish for all heights the forces under field and ocean conditions combined with roll and pitch motions. From this analysis it became clear overall field forces can be described as a percentage of ocean forces between 42% and 45%. Roll motions can be described as two times pitch conditions. So the forces can roughly be obtained by the factors from Table 11. With use of this table it is possible to gather all exerting forces in the system. The bending moment and shear force distributions are shown in Figure 41[31].

[30] For insight in the signs used in this section and in DNV-rules please refer to section 11.4
[31] The meaning of mu does not belong to the scope of this thesis, but can be found in Det

| | Pitch | Roll |
|---|---|---|
| Ocean | 5 | 2.5 |
| Field | 2 | 1 |

Table 11: Relations between conditions

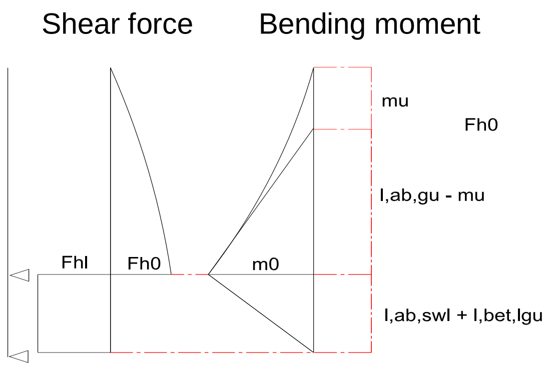


Figure 41: Two fixation point: Shear force and bending moment distribution

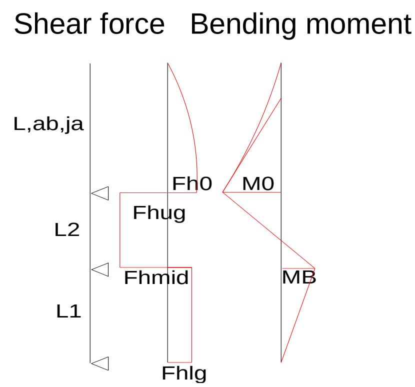


Figure 42: Three fixation point: Shear force and bending moment distribution

### 11.2.4 Three fixation points[32]

To enable more possibilities a 3 fixation point system needs to be considered as well. For calculation one fixation point is taken as a hinge and the other two as rollers. The force distribution along those three points can be determined according to the distribution model outlined in Figure 43. The relieving moment $M_{fug}$, can be determined according to $\varphi_{fug} = \varphi_{flg}$. From this only the static conditions are needed to obtain the formulas for $F_{hlg}$, $F_{hug}$ and $F_f$ if $L_{abjah}$ and $L_1$ are taken as variables.

NB: The horizontal and vertical forces arising from the environment are not considered in this calculation, only the bending moment, the horizontal force $F_{h0}$ has to be increased by $F_{hug}$ and the vertical force gets to the vertical fixation force in the hinge.

Derivation relieving moment $M_{fug}$:

$$\varphi_{lg} = \frac{M_{fug} \cdot l_1}{3EI} = \varphi_{ug} = \frac{M_{fug} \cdot l_2}{3EI} - \frac{M_0 \cdot l_2}{6EI}$$

$$2M_{fug} * l_1 = 2M_{fug} * l_2 - M_0 * l_2$$

$$M_{fug} = \frac{0.5 \cdot M_0 \cdot l_2}{(l_1 + l_{2)}}$$

Horizontal reaction forces:

$$F_{hlg} = \frac{M_{fug}}{l_1}$$

$$F_{hug} = \frac{M_0 + M_{fug}}{l_2}$$

$$F_f = -\left[\frac{M_0 + M_{fug}}{l_2}\right] - \left[\frac{M_{fug}}{l_1}\right]$$

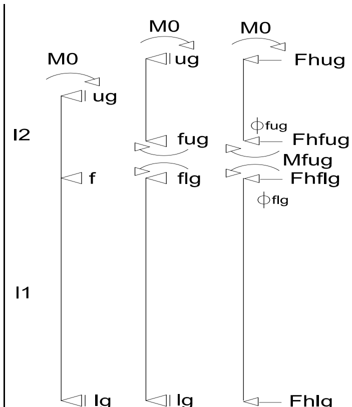


Figure 43: Three fixation point: Force distribution

Norkse Vertias (1992, blz. 16).
32 $L_{ab,jah}$ is the same in this calculations as $L_{abgu}$

Again for every height $L_{abjah}$ the horizontal forces are calculated for every fixation point and a variable height between the lower and middle fixation point ($L_1$). The results are shown in Figure 44 for the upper, Figure 45 for the middle and Figure 46 for the lower fixation point.

Again it seemed field forces can be described as 40% of the ocean forces. Forces arising from roll movements can be described as 50% of the forces arisen from pitch. From which the reference is again made to Table 11. The bending moments and shear forces for three fixation points can be described according to Figure 42[33].

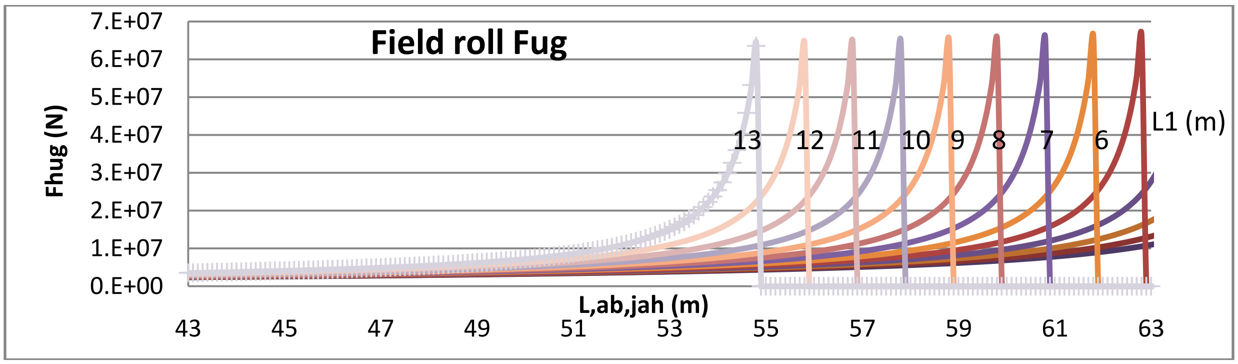


Figure 44: Three fixation point analysis, field roll upper fixation point

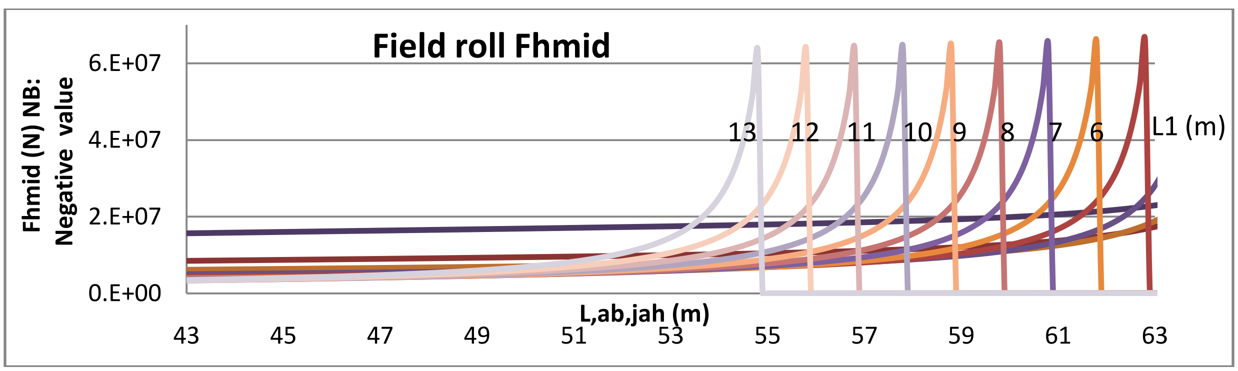


Figure 45: Three fixation point analysis, field roll middle fixation point

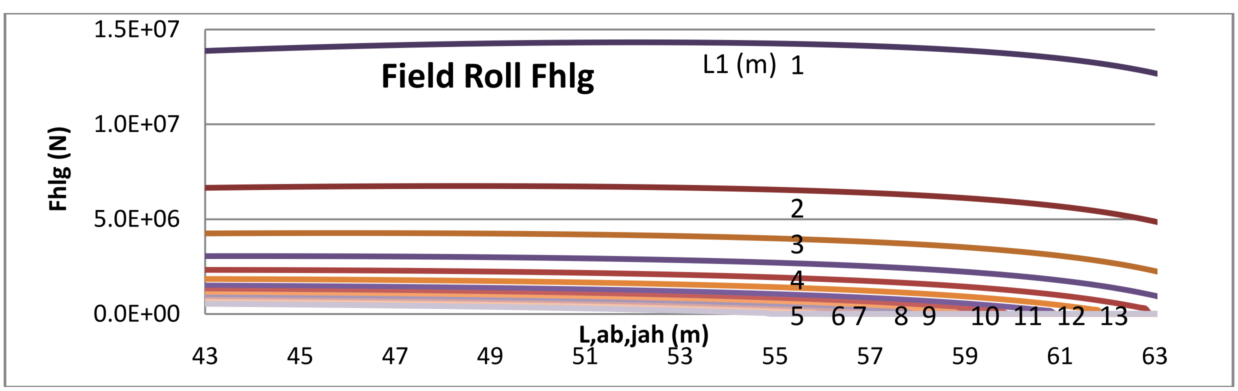


Figure 46: Three fixation point analysis, field roll lower fixation point

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33 $M_{fug} = M_b$

### 11.2.5 Analysis

*To gain conclusions from the data acquired in previous sections it is necessary to analyze the data. This is again separated for two and three fixation points. Also a quick calculation is given to prove the legs ability to withstand bending moments arisen from environmental conditions.*

#### 11.2.5.1 Two fixation points

When analyzing the data from the two fixation point analysis the maximum and minimum horizontal forces in the upper and lower fixation point can be established. For field roll the value lays between 1.4MN and 9.0MN. The forces for the other conditions can be established according to the tables in the previous chapter. The same applies to the lower guide, except the values for field roll are between -1MN and -8MN.

From the graphs in the previous chapter it becomes clear that real difference in horizontal force are starting to arise between $L_{ab,jah}$ = 53 and 57 meter. When referring to the design of the Bard jacking house, with $L_{ab,jah}$ = 54 meter, this means rising the upper fixation point wouldn't make a great difference in horizontal force, but lowering the upper fixation point could significantly increase the horizontal force. Care has to be taken to draw straight conclusions here because problems can arise from the location of the jacking systems, which will be analyzed in the section 11.7: "Available space in jacking house and guide structure"

#### 11.2.5.2 Three fixation points

The analysis of three fixation points is somewhat more difficult due to the extra degree of freedom. Due to this it is necessary to analyze three graphs (which were shown in the previous paragraph), instead of one graph with two points. It becomes quite clear from these graphs that the force in the lower fixation point is for the largest part determined by the distance $L_1$ between the lower fixation point and the middle one. This, of course, also means that it depends on the distance $L_2$ between the middle fixation point and the upper one, because they are connected referring to $L_{ab,jah}$.

Reason for the application of three fixation points instead of two could be lack of space. When referring to the data for two fixation points data above 9MN can be removed, because it would increase the force in the upper guide to much. Figure 47 is a result from this.

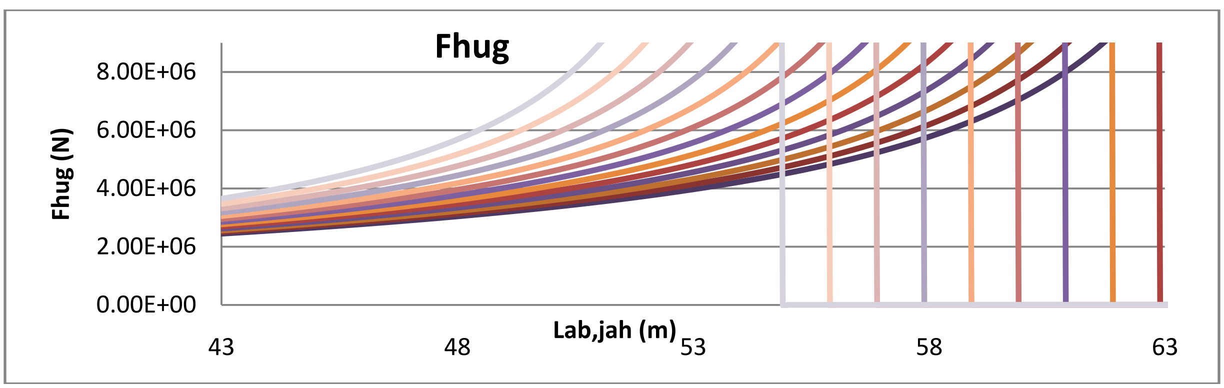



Figure 47: Three fixation point analysis: upper fixation point below 9MN

When referring to the graph the conclusion can be stated that relieving the upper guide with an extra fixation point would fail, which is reasonable when referring to the bending moment distribution in the previous chapter. An extra bending moment is introduced due to the extra fixation point and will increase the forces in the fixation points accordingly. The same principle works for the middle fixation point. Though it might be possible three fixation point arrangements carry some design possibilities or are easier to implement.

#### 11.2.5.3 Bending Resistance

It is interesting to determine the legs ability to withstand the maximum bending moment arising from the environment. The maximum calculated bending moment at the midsection ($M_b$) was 6.86E7 Nm. The maximum bending moment the legs can resist has to be determined according to the next formula:

$$M_{out} < M_{in} = f_{y,d} \cdot W_{y,el}$$

For rough calculation the assumption for the resistant moment ($W_{y,el}$) is made to be calculated according to the formula of I-beams[34]. The bending resistance of the legs is calculated in attachment 11.4 as 1.68E12mm$^4$. For correct rough calculation the following assumptions are made: bending resistance as 0.9E12 mm$^4$ and height as 2.8 m (height center of gravity of the racks). The steel quality is taken as S355. From this it is possible to calculate the internal bending moment (maximum applicable moment to the structure) which has to be higher than the external bending moment.

$$M_{out} < M_{in} = f_{y,d} \cdot W_{y,el} = f_{y,d} \cdot \frac{I_{y,el}}{0.5\ h} = 355 * \frac{0.9E12mm^4}{0.5 * 2800mm} = 2.28E8\ Nm > 6.86E7\ Nm$$

So according to the bending resistance of the leg, which is calculated conservative, it is possible to maintain 3 fixation points for every situation.

[34] Which would not be entirely correct, but the main part of the bending resistance of the leg arises from the outer rims (0.9 out of 1.7 mm$^4$).

## 11.3 FORCE ANALYSIS, LEG CALCULATION: GENERAL DESCRIPTIONS

If the mass of the leg is assumed to be evenly distributed along the length of the leg it is possible, according to the method described in Det Norske Veritas (1992, par. 5.3.6), to determine the forces existing from wind, waves, current and inertia with to the formulas as cited in Table 12. The heights these forces are working on are also cited in this table. The signs are shown in attachment 11.4. Used values are described in Table 13

| **Force:** | **Force calc:** | **Acting at:** |
|---|---|---|
| Transverse static force | $F_{ts} = \mathrm{m}_{\mathrm{ab,gu}} \cdot \mathrm{g} \cdot \sin\theta_0$ | $x_s = l_{ab,jah} \cdot \left(0.5 + \frac{\mathrm{l}_{\mathrm{ab,swl}}}{\mathrm{l}_{\mathrm{ab,jah}}}\right)$ |
| Transverse inertia force | $F_{td} = \mathrm{m}_{\mathrm{ab,gu}} \cdot \varepsilon_0 \cdot \mathrm{l}_{\mathrm{ab,jah}} \cdot \left(0.5 + \frac{\mathrm{l}_{\mathrm{ab,swl}}}{\mathrm{l}_{\mathrm{ab,jah}}}\right)$ | $x_d = \frac{2}{3} \cdot l_{ab,jah} \cdot \frac{1+3\cdot\left(\frac{\mathrm{l}_{\mathrm{ab,swl}}}{\mathrm{l}_{\mathrm{ab,jah}}}\right)+3\cdot\left(\frac{\mathrm{l}_{\mathrm{ab,swl}}}{\mathrm{l}_{\mathrm{ab,jah}}}\right)^2}{1+2\cdot\left(\frac{\mathrm{l}_{\mathrm{ab,swl}}}{\mathrm{l}_{\mathrm{ab,jah}}}\right)}$ |
| Transverse wind force | $F_w = \frac{\mathrm{c}_{\mathrm{wind}}}{2} \cdot \rho \cdot \mathrm{C}_{\mathrm{drag}} \cdot \mathrm{D}_{\mathrm{leg}} \cdot \mathrm{v}_{\mathrm{r}}^2 \cdot \mathrm{z}_0$ | $x_w = \frac{z_w - z_{lep}}{\cos\theta_0}$ |
| Longitudinal static force | $F_{ls} = \mathrm{m}_{\mathrm{ab,gu}} \cdot \mathrm{g} \cdot \cos\theta_0$ | $x_s$ |
| Longitudinal inertia force | $F_{ts} = \mathrm{m}_{\mathrm{ab,gu}} \cdot \varepsilon_0 \cdot 0.5 \cdot \mathrm{b}_{\mathrm{c-c,leg}}$ | $x_d$ |

Table 12: Formulas for forces applied to legs

Explanation of signs:

$$\varepsilon_0 = \left(\frac{2\cdot\pi}{T_0}\right)^2 \cdot \theta_0$$

$D_{leg}$ = characteristic cross-sectional dimension of the leg

$$c_{wind} = 0.85 \cdot \cos\theta_0 \cdot \left[\left(\frac{z_h}{z_0}\right)^{1.18} - \left(\frac{z_l}{z_0}\right)^{1.18}\right]$$

$$z_w = 0.54 \cdot z_0 \cdot \frac{\left(\frac{z_h}{z_0}\right)^{2.18} - \left(\frac{z_l}{z_0}\right)^{2.18}}{\left(\frac{z_h}{z_0}\right)^{1.18} - \left(\frac{z_l}{z_0}\right)^{1.18}}$$

$z_l$ = vertical distance from still water level to lower exposed point of the leg (upper side of lower fixation point).
$z_h$ = vertical distance from still water level to top of the leg.
$z_0$ = reference height
$v_r$ = reference wind velocity

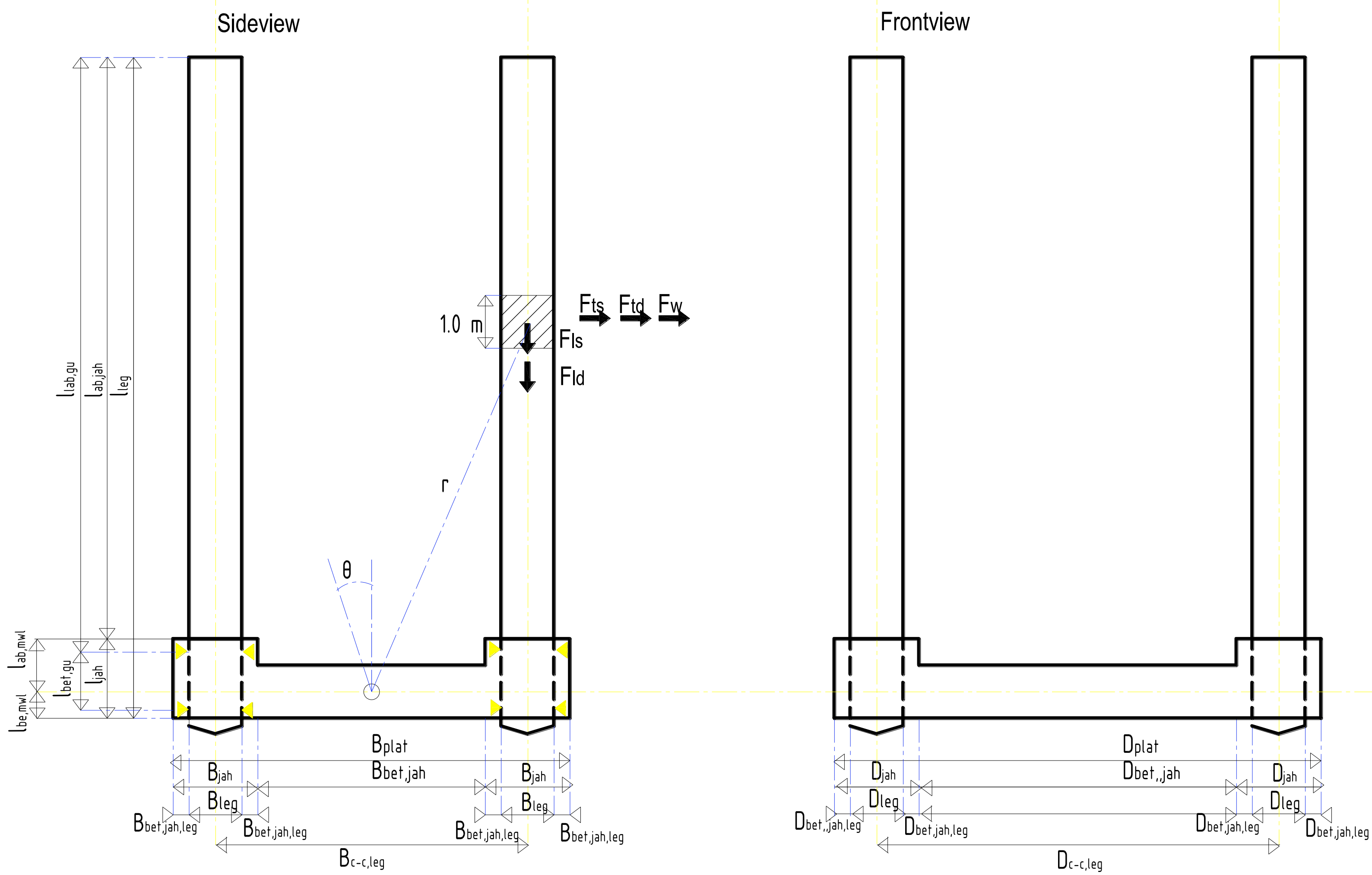
| Symbol | value | Unit |
|---|---|---|
| $m_{ab,gu}$ | Variable (according to location of upper fixation system ($l_{ab,gu}$ * 6700kg/m) | kg |
| $g$ | 9.81 | $m/s^2$ |
| $\theta_0$ | For field transit: 6<br>For ocean transit: 15 | $^0$ |
| $l_{ab,jah}$ | 54.220 for Bard I | m |
| $l_{ab,swl}$ | | m |
| $T_0$ | For roll: 12.7<br>For pitch: 7.5 | s |
| $\rho$ | 1.225 | $kg/m^3$ |
| $C_{drag}$ | 1.3 | |
| $D_{leg}$ | 4.09 | m |
| $v_r$ | For field transit: 38<br>For ocean transit: 52 | m/s |
| $z_0$ | 10 | m |
| $b_{c\text{-}c,leg}$ | For roll: 50.400<br>For pitch: 28.800 | m |
| $z_l$ | Variable according to location of upper fixation system (SWL = 3.60 m) | m |
| $z_h$ | 67.600 | m |
| $z_0$ | 10 | m |
| $l_{ab,gu}$ | Variable according to location of upper fixation/ upper guide | m |
| $L_{bet,lgu\text{-}swl}$ | Distance between lower fixation point (evt. guide and swl) | m |

Table 13: Used values leg force calculation DNV

The forces are variable on the distance between the fixation points and the distance between the upper fixation point and the SWL. Also are the forces variable on the loading conditions concerning rolling of pitching and ocean and field transit conditions. Last but not least the forces are variable on the arrangements of the fixation points (hinges or rollers).

To perform calculation the mechanics system is simplified by leaving of the cantilever part of the legs, and replacing them by a horizontal force, vertical force and bending moment at the top of the upper guide/ fixation system.

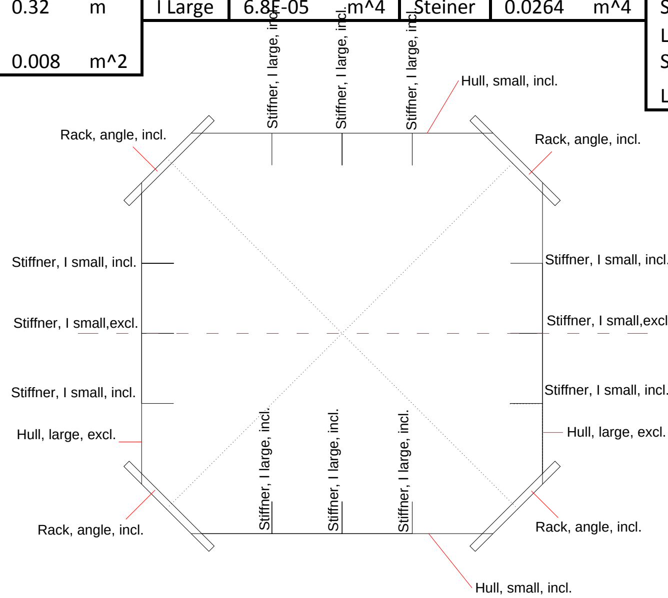
## 11.4 FORCE ANALYSIS, SIGNS DNV FORCE ANALYSIS IN TRANSIT CONDITIONS



## 11.5 FORCE ANALYSIS, BENDING RESISTANCE LEGS

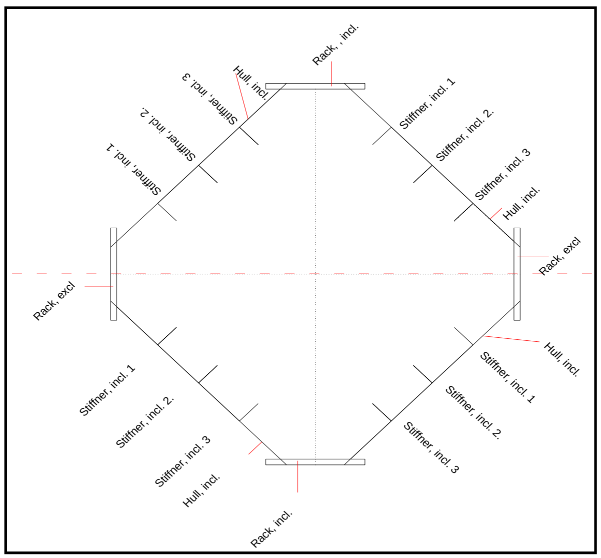
**Calculation moment of inertia of Bard II legs:**

| Legpart | dimension | value | unit | I | | | | | | | Amount: | I | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rack | *b* | 0.075 | m | Angle | 0.0027 | m^4 | Steiner | 0.2601 | m^4 | Excl. Steiner | 0 | 0.000 | |
| | *h* | 1.2 | m | | | | | | | Incl. Steiner | 4 | 1.051 | |
| | *A* | 0.09 | m^2 | | | | | | | | Total Rack | 1.051 | |
| Hull | *b* | 0.025 | m | I Small | 3.6E-06 | m^4 | Steiner | 0.2765 | m^4 | Small Excl. Steiner | 0 | 0.000 | |
| | *h* | 2.8 | m | I Large | 0.04573 | m^4 | Steiner | 0 | m^4 | Small Incl. Steiner | 2 | 0.553 | |
| | | 0.07 | m^2 | | | | | | | Large Excl. Steiner | 2 | 0.091 | |
| | | | | | | | | | | Large Incl. Steiner | 0 | 0.000 | |
| | | | | | | | | | | | Total Hull | 0.644 | |
| Stiffners | *b* | 0.025 | m | I Small | 4.2E-07 | m^4 | Steiner | 0.0038 | m^4 | Small Excl. Steiner | 2 | 0.000 | |
| | *h* | 0.32 | m | I Large | 6.8E-05 | m^4 | Steiner | 0.0264 | m^4 | Small Incl. Steiner | 4 | 0.015 | |
| | | 0.008 | m^2 | | | | | | | Large Excl. Steiner | 0 | 0.000 | |
| | | | | | | | | | | Large Incl. Steiner | 6 | 0.159 | |
| | | | | | | | | | | | Total Stiffners | 0.174 | |
| | | | | | | | | | | | Total | **1.869** | m^4 |
| | | | | | | | | | | | | **1.869E+12** | mm^4 |



**Calculation moment of inertia of Bard II legs:**

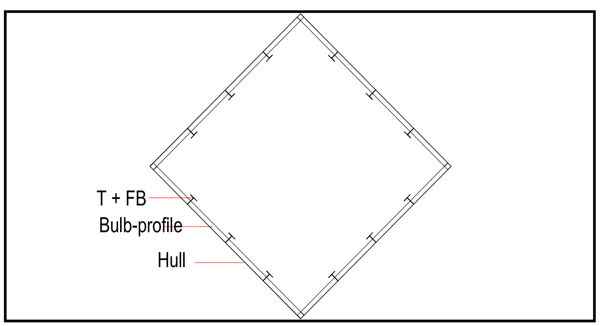
| Legpart | dimension | value | unit | | | | | | | | Amount: | I |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rack | *b* | 0.075 | m | I small | 4.21875E-05 | m^4 | Steiner | 0.4582052 | m^4 | Large Excl. Steiner | 2 | 0.022 |
| | *h* | 1.2 | m | I large | 0.0108 | m^4 | Steiner | 0 | m^4 | SmallIncl. Steiner | 2 | 0.916 |
| | *A* | 0.09 | m^2 | | | | | | | | Total Rack | 0.938 |
| Hull | *b* | 0.025 | m | I angle | 0.011433333 | m^4 | Steiner 1 | 0.1399577 | m^4 | Angle incl. Steiner | 4 | 0.606 |
| | *h* | 2.8 | m | | | | | | | | 0 | 0.000 |
| | | 0.07 | m^2 | | | | | | | | 0 | 0.000 |
| | | | | | | | | | | | 0 | 0.000 |
| | | | | | | | | | | | Total Hull | 0.606 |
| Stiffners | *b* | 0.025 | m | I angle | 1.70667E-05 | m^4 | Steiner 1 | 0.0051842 | m^4 | Angle incl. 1 | 4 | 0.021 |
| | *h* | 0.32 | m | | | | Steiner 2 | 0.0136242 | m^4 | Angle incl. 2 | 4 | 0.055 |
| | | 0.008 | m^2 | | | | Steiner 3 | 0.0144 | m^4 | Angle incl. 3 | 4 | 0.058 |
| | | | | | | | | | | | 0 | 0.000 |
| | | | | | | | | | | | Total Stiffners | 0.133 |
| | | | | | | | | | | | Total | **1.677m^4** |
| | | | | | | | | | | | | **1.677E+12mm^4** |

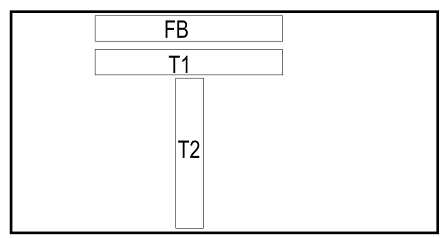


## 11.6 FORCE ANALYSIS, BENDING RESISTANCE JACKING HOUSE

**Calculation moment of inertia of Bard II jacking house:**

| part | dimension | value | unit | I | value | dimension | I steiner | value | dimension | | Amount: | I |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hull | *d* | 0.015 | m | angle | 0.11664 | m^4 | | 0.549846233 | m^4 | angle, incl. | 4 | 2.6659449 |
| | *l* | 7.2 | m | | | | | | | | | |
| | *A* | 0.108 | | | | | | | | | | |
| T + FB | *dT1+dFB* | 0.035 | m | angle T1+fb | 5.8333E-06 | m^4 | 1.1 | 0.0083167 | m^4 | angle T1+fb, incl | 4 | 0.0332901 |
| | *lT1/dFB* | 0.2 | m | angle T2 | 0.00001458 | m^4 | 1.2 | 0.0376768 | m^4 | angle T1+fb, incl | 4 | 0.1507305 |
| | *dT2* | 0.015 | m | Itotaal | 2.0413E-05 | | 1.3 | 0.0912247 | m^4 | angle T1+fb, incl | 4 | 0.3649571 |
| | *lT2* | 0.36 | m | | | | 2.1 | 0.0071415 | m^4 | angle T2, incl | 4 | 0.0285893 |
| | *AT1+FB* | 0.007 | m^2 | | | | 2.2 | 0.03188646 | m^4 | angle T2, incl | 4 | 0.1275692 |
| | *AT2* | 0.0054 | m^2 | | | | 2.3 | 0.07472736 | m^4 | angle T2, incl | 4 | 0.2989328 |
| | *Atotaal* | 0.0124 | m^2 | | | | | | | | | |
| Bulb | *d* | 1.60E-01 | m^4 | angle | 1.24E+00 | m^4 | | 5.87E+00 | | | 4 | 2.84E+01 |
| | *l* | 7.2 | m^4 | | ref 1 | | | | | | | |
| | *A* | 1.15E+00 | m^4 | | | | | | | | | |

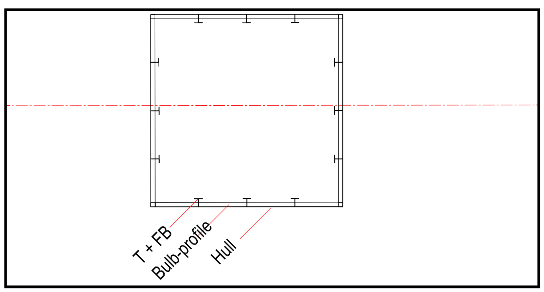



| | | |
|---|---|---|
| Total hull | 2.6659449 | m^4 |
| Total T+FB | 1.0040691 | m^4 |
| Total bulb | 2.84E+01 | m^4 |
| Total | 32.10676 | m^4 |

**Calculation moment of inertia of Bard II jacking house:**

| part | dimension | value | unit | I | value | dimension | I steiner | value | dimension | | Amount: | I | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hull | *d* | 0.015 | m | small. | 2.03E-06 | m^4 | small | 1.40E+00 | | small | 2 | 2.80E+00 | |
| | *l* | 7.2 | m | large | 4.67E-01 | | | | | large | 2 | 9.33E-01 | |
| | *A* | 0.108 | | | | | | | | | | | |
| T + FB | *dT1+dFB* | 0.035 | m | small t1 +dFB | 7.14583E-07 | m^4 | small | 0.040176 | m^4 | excl | 2 | 4.68692E-05 | |
| | *lT1/dFB* | 0.2 | m | large t1 +dFB | 2.33333E-05 | m^4 | large T1 + FB | 0.07623 | m^4 | incl small | 4 | 0.160797738 | |
| | *dT2* | 0.015 | m | small T2 | 1.0125E-07 | m^4 | Large T2 | 0.0642735 | m^4 | incl large | 6 | 0.843375208 | |
| | *lT2* | 0.36 | m | large T2 | 0.00005832 | m^4 | | | m^4 | | | | |
| | *AT1+FB* | 0.007 | m^2 | | | | | | m^4 | | | | |
| | *AT2* | 0.0054 | m^2 | | | | | | m^4 | | | | |
| | *Atotaal* | 0.0124 | m^2 | | | | | | | | | | |
| Bulb | *d* | 1.60E-01 | m^4 | small. | 2.46E-03 | m^4 | small | 1.49E+01 | | small | 2 | 2.99E+01 | |
| | *l* | 7.2 | m^4 | large | 4.98E+00 | | | | | large | 2 | 9.95E+00 | |
| | *A* | 1.15E+00 | m^4 | | | | | | | | | | |
| | | | | | | | | | | | Total hull | 2.79936405 | m^4 |
| | | | | | | | | | | | Total T+FB | 1.004219815 | m^4 |
| | | | | | | | | | | | Total bulb | 2.99E+01 | m^4 |
| | | | | | | | | | | | Total | 33.66833907 | m^4 |



## 11.7 AVAILABLE SPACE IN JACKING HOUSE AND GUIDE STRUCTURE

*When designing a leg sea fastening system for jack ups it is reasonable to assume the system located in the jacking house. Although this is not primarily a design criterion, it is reasonable to have a closer look at the jacking house structure, and in more detail the guiding structures, which are located in the jacking house for Bard I. This is reasonable because a two fixation point structure should mostly include one or more guides or at least their location. Primary objective here is to establish the spacing (un-)suitable for a new system; secondary objective is to determine some basic force resisting capabilities from the jacking house.*

### 11.7.1 Guiding structure

*The guides of a jack up are stiff structures which are guiding the leg through the jacking house restricting the legs movement but still maintaining the legs possibility to be jacked. The main features of the guiding system for the leg sea fastening system are primarily related to the available spacing. The establishment of the spacing around the guides should not mainly be influenced by the fixation system used on the Bard-project, as described in section 2.3.*

#### 11.7.1.1 Lower guides

The lower guide system is shown in . The picture shows a top view of the lower guide structure. The only limiting factors in this part of the jacking house are the guide structures, the stiffening profile and the jacking system supports, including the eyes of the jacking structure (not shown). It can be concluded that there is space for fixation elements around those systems. This space is marked with black dots[35]. Although fixation is possible at those locations, some care has to be taken according to the applicability at those locations because of the force baring capability of the leg; because the hull of the leg is less force resistant than the racks. Restrictions are not made for this limitation because extra stiffening of the legs at the fixation level might be possible.

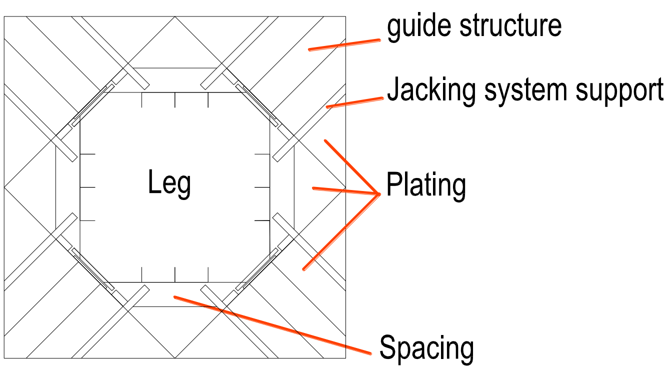



Figure 48: Lower guide, top view

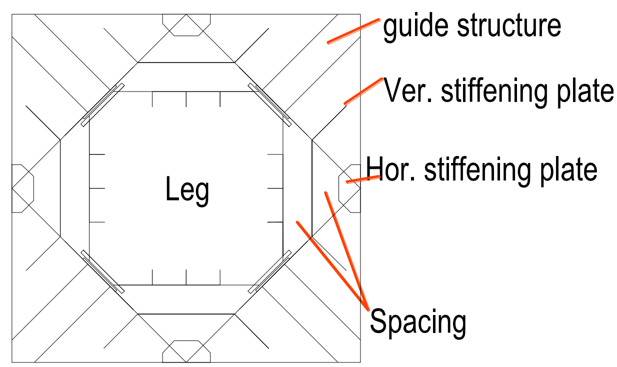



Figure 49: Upper guide, top view

#### 11.7.1.2 Upper guides

The upper guide structure, which is displayed in Figure 49, looks merely the same as the lower guide structure except from the jacking support system and additional stiffening, which is necessary because, instead of the hull of the platform surrounding the lower guide, the upper

[35] Symmetry can be applied.

guide is surrounded only by air. The plan view is made at 15.430 meter from base at Bard I, the lower sections of the guiding structure are the same, with the difference that plating and horizontal stiffening are excluded. This means availability of a lot of space around the upper guides.

### 11.7.2 Space between the guides

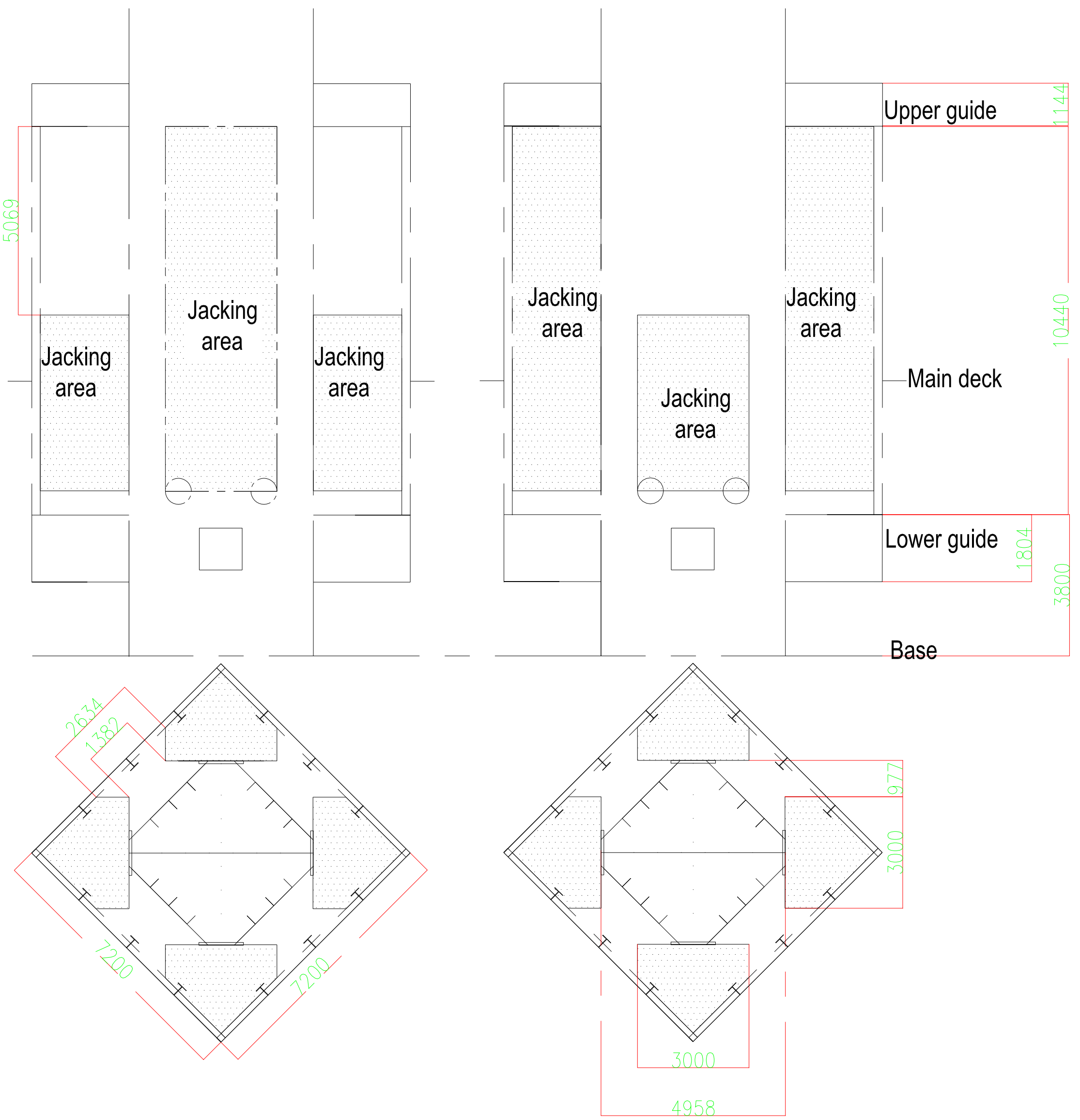
*Between the lower and upper guide there are lots of space, but it also contains the jacking systems, hence a closer look at this section of the jack up would be necessary. The space above the upper guide is free and beneath the lower guide there are only the spudcan and its guidance and is hence not much of an interest.*

The design of the new system according to the Bard I project involves a “pin and hole” jacking system which is fully enclosed by the hull of the jacking house. The system is thereby completely placed between the guides. The jacking system contains of a pair of low cylinders and a pair of high cylinders, meaning two with a long reach at two opposite racks and two with a short reach at the other two opposite racks. This leaves space above the short reach cylinders, but none above the long reach cylinders. Of course extra room is available between the yokes of the jacking systems (the pins of the pin and hole system). In the attachment 11.8 the available space has been drawn, the dotted areas are not available for the fixation system due to the reach of the jacking system. Care has to be taken in the design to remain the possibility to exchange parts of the jacking system. When the leg is fully retracted one pair of jacking cylinders can be used to drive a part of the sea fastening system. The jacking cylinders can only be used in the vertical direction.

The section just below the upper guide, guiding the forces from the upper guide to the jacking house, only contains of plating at the outer rim of the guide structure, 7200 x 35 mm plating. Due to the large size of the square, 7200 x 7200 mm, with its corresponding moment of inertia[36] it would be resistant enough to guide the forces downwards.

[36] Moment of inertia jacking house: Approximately 2.6 $m^4$, listed as hull in attachment 11.6

## 11.8 AVAILABLE SPACE, JACKING HOUSE, SIDE AND TOP VIEWS



## 11.9 FIELD OF SEARCH, SYSTEMS

*The possibilities to secure the legs to the platform are endless. To gain knowledge about the main fields of search a small survey has been made to applicable driving systems and clamping techniques. The driving techniques are driving the clamping units. Another possibility is the usage of passive elements, which could be explained as parts of the construction of the jacking house, primarily used in the LSFS configuration or primary parts of the LSFS configuration other than clamping. It is possible to make this analysis primary on the application in a certain system, nevertheless a broad view could increase the, creative, possibilities.*

### 11.9.1 Driving techniques

*Leg sea fastening is mostly done by active systems. To be able to sea fasten the legs different power sources can be applied. The main distinction can be made between linear systems and rotating systems. Although some options do not seem to reach a straight forward application for the new LSFS, it might be an eye opening opportunity and hence they are mentioned.*

#### 11.9.1.1 Linear systems

Figure 50: Piezo linear motor

One of the possibilities is shown in Figure 50; this is a piezo linear motor as shown at PI (n.d.). Although the force which can be delivered by this system is limited to 400N, the precision is very high (within a nanometer). This makes it possibly more feasible in the precision industry, and not for this new LSFS.

Another possibility is the use of hydraulic cylinders, which is more common in the leg sea fastening systems. Major advantage of hydraulic cylinder is the capability to apply a large amount of pressure with a considerable stroke. According to Mannesmann-Rexroth (n.d.) the maximum force which can be applied by one standard 320 bar cylinder is 3257kN with a piston diameter of 500mm, a piston rod diameter of 360mm, and a maximum buckling length (Euler) of approx. 13 meters.

According to the same principle it is possible to make use of the already available pin and hole jacking system cylinders to secure the legs to the hull. When making use of the jacking system in combination with, for example block and tackle configurations, it might be possible to control the movements of the jack-up legs.

Hydraulic cylinders can also be applied, as in the Bard project, to push against the leg or by means of pushing something inside or even through the leg. When the cylinder is operating in the longitudinal direction and the force applied to a bar, which was pushed through the leg, operating in the transverse direction this might reduce the force endured by the cylinder.

When making use of crankshaft systems, linear systems can be applied for rotational movements (and vice versa). This application is most interesting when a 360 degree rotation is not necessary.

For linear clamping it is also possible to make use of magnetic systems. By applying a magnetic field to the jack up leg, it is possible to maintain its position or attract the leg to one side. According to www.walkermagnet.com, retrieved on 23-06-2008 it is possible, with products in their product range, to hoist materials over 125.000lbs (approx. 5.8kN) with one system.

It is also possible to make use of air cushions. Advantage is the possibility to spread the force over a large surface. Aircushions of 1000*245*30 mm at 10 bar are able to withstand a force of 129kN. Possible larger pressures can be applied. All data is according to www.aerofilmsystems.com (n.d.)

#### 11.9.1.2 Rotating systems

A sea fastening of legs can be done by rotating parts, which can be applied as rotating parts itself or by activating a lateral movement (crankshaft principle or rack and pinion).
Diverse possibilities are arising with rotating systems e.g. electro & diesel engines. When making use of worm wheels the force applied will be much larger, and the system would not be able to disengage itself, hence correct designed. This can be compared to the bench vise principle. Worm wheels are a special type of cogwheels; all kind of cogwheels can be applied. To provide the correct amount of force and speed at the right place it might be necessary to apply one or more cogwheels.

When talking about cable/ belt drives, it would be necessary to apply winches. These can be delivered in almost every size and capabilities.

### 11.9.2 Passive elements

It might be resourceful making use of just passive elements for the LSFS reducing operating costs. The lower part of the leg is secured in this way by making use of the wedge shaped contours of the spudcan interacting with the wedge shape of the guides. In this way the upward motion of the leg (by the jacking system) is used to secure the leg. This also may be possible for the upper part of the leg.

It is also possible to make use of wooden wedges, as in the traditional method. Although the system has to be replaced according to the scope of this thesis, the same principle may work in an automatic version. The application of wood can be done considering a maximum of the pressure strength up to 34 N/mm$^2$ when the force is applied axial through the wood fibers.

The main application of the LSFS would be to stop the legs from hitting the guides. Instead of clamping the leg, only suspending could be an opportunity. According to www.trelleborg.com (n.d.), the maximum compression stiffness is 70000kN/m (dynamic force) at their Metalistik type Sandwich mountings, but can only take 417 kN axial loading. Although the mentioned system is used to suspend engines it illustrates a possibility for shock absorbing.

### 11.9.3 Clamping systems

In order to secure the legs diverse clamping techniques can be applied. One possible shape was according to Asd security equipment gmbh (n.d.) as shown in Figure 51:

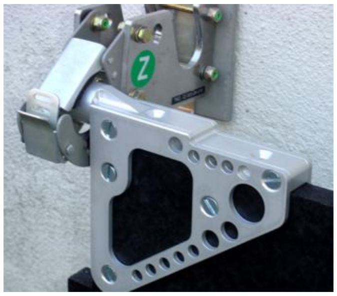


Figure 51: Clamping system (naval-technology)

The system is of 2 half sides clamping the tube on the plating (which could be the leg) like jaws. Because the leg has to be able to move freely when the LSFS is disengaged, clamping shapes like Figure 52, from Aubuchon hardware (n.d.), would do the trick. Although when opened the element inside is able to move freely, when closed all directions of movement can be cut off.

Figure 52: Clamping system (hardwarestore)

Though both systems are designed for much smaller applications, the principle might work in a scaled arrangement combined with active systems.
A simpler solution is making use of band clamping as shown in Figure 53, which was gathered from the Adjustable clamp company (n.d.), although a simple principle, concentrated forces in the leg may arise.

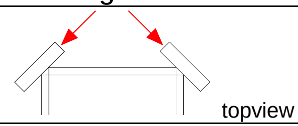
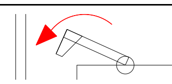
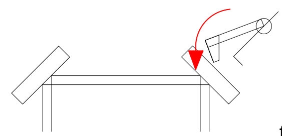
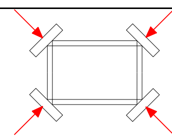
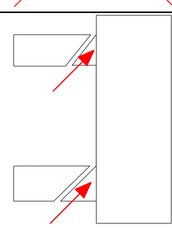
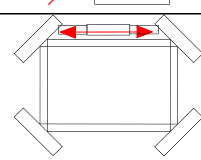
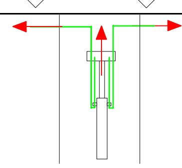
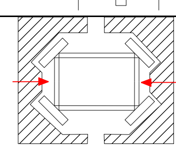
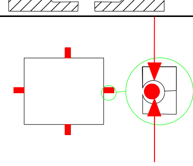

Figure 53: Band clamping

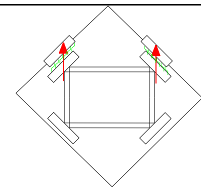
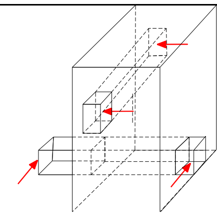
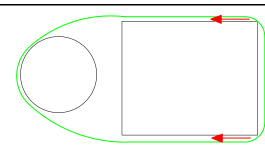
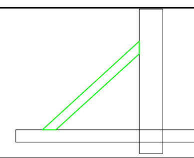
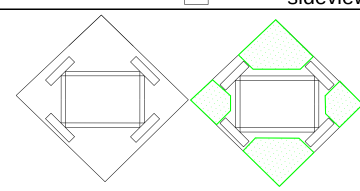
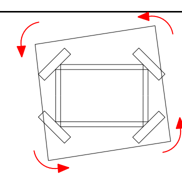
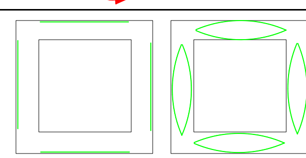
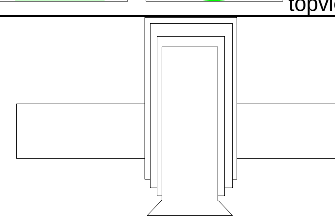
Although not really passive, the application of rope and sheaves may be an option to guide the forces through the jacking house to the platform. Major advantage is the possibility to make use of the force applied by the jacking system to sea fastens the legs e.g. by attaching the rope to the yoke. A disadvantage is, like the band clamping system, the extra care which has to be taken to prevent from concentrated forces in the legs, due to the small size of the rope, and thereby causing the failure of the leg.

## 11.10 FIELD OF SEARCH, PRINCIPLES

*From brainstorming several basic principles have been discovered to ensure leg sea fastening. Those principles are based on the systems described in the previous chapter. By means of a really short description and drawing of the principle a small insight is given. Main features of those systems are compared at a uncomplicated level with a Multi Criteria Analysis (MCA).*

### 11.10.1 Principles

| Principle | Drawing |
|---|---|
| **Rack enclosure:** By means of pushing against the sides of the racks. Based on the CJ-fixation system. |  topview |
| **Wooden blocks top variant**: Swing in a block from above. |  sideview |
| **Wooden blocks side variant:** Rotating a block sideways between rack and structure. |  topview |
| **Bard I variant:** Pushing against four racks instead of two. |  topview |
| **Double wedge:** Also a wedge shape at upper guide. Based on the Mayflower Resolution system. |  sideview |
| **Inside clamping:** Clamping two opposite racks from inside. |  topview |
| **Cable jacking system:** Using the jacking system combined with block and tackle systems. |  sideview |
| **Leg clamp (hardwarestore variant):** Using 2 clamping parts clamping the leg. |  topview |
| **Leg clamp (naval-technology variant):** clamping small out sticking pieces of the leg. |  topview - sideview |

| | |
|---|---|
| **Electro magnet:** Using an electromagnetic field to force the leg to stay at one side. |  topview |
| **Tunneling variant:** Driving piles through tunnels inside the leg. |  3D-view |
| **Band clamping:** Using a band to strap the leg to one side. |  topview |
| **Supporting:** Using large supports to secure the leg. |  sideview |
| **Leg trap:** Using a larger piece of rack at the bottom to trap the rack between the structure when lifted. |  topview |
| **Wrench:** By rotating a structure clamping the leg like a vice. |  topview |
| **Air cushion:** By inflating several cushions encapsulating the leg. |  topview |
| **Telescopic legs:** This principle is according to Scales R.E. (1976), a system to retract the pile within the platform so the forces would not even occur. |  sideview |

### 11.10.2 Multi criteria analysis: Principles:

To be able to compare the principles and to make a choice which should be elaborated a multi criteria analysis has been conducted. Although the analysis is for the great part based on intuition and estimation the impossible or very undesirable alternatives could be taken out. The principles are compared at each of the following criteria: Safety, Reliability, Operation (total of men involved), Costs, Engagement time and Calculation time. The outcome is shown in Table 14: MCA principles

**Unweighted, unstandardized table**

| Principle | Safety | Reliability | Operation | Costs | Engagement time | Calculation time |
|---|---|---|---|---|---|---|
| Bard I system | 0.8 | 0.9 | 1 | 0.6 | 0.7 | 0.8 |
| Rack enclosure | 0.9 | 1.0 | 1 | 0.5 | 0.6 | 0.8 |
| Wooden blocks | 0.9 | 0.9 | 1 | 0.6 | 0.7 | 0.7 |
| Bard I variant | 0.8 | 0.8 | 1 | 0.4 | 0.6 | 0.8 |
| Double wedge | 0.8 | 1.0 | 0 | 0.8 | 1 | 0.5 |
| Inside clamping | 0.6 | 0.8 | 1 | 0.4 | 0.4 | 0.4 |
| Cable jacking system | 0.8 | 0.5 | 2 | 0.9 | 0.4 | 0.5 |
| Leg clamp (hardware store variant) | 0.9 | 0.9 | 1 | 0.5 | 0.7 | 0.7 |
| Leg clamp (naval-technology variant) | 0.7 | 0.5 | 2 | 0.5 | 0.4 | 0.4 |
| Electro magnet | 0.5 | 0.4 | 1 | 0.4 | 0.9 | 0.9 |
| Tunneling variant | 0.6 | 0.5 | 3 | 0.4 | 0.4 | 0.5 |
| Band clamping | 0.8 | 0.6 | 2 | 0.9 | 0.7 | 0.8 |
| Supporting | 0.5 | 0.4 | 3 | 0.8 | 0.4 | 0.5 |
| Leg trap | 0.7 | 1.0 | 0 | 0.8 | 1 | 0.7 |
| Wrench | 0.3 | 0.3 | 1 | 0.5 | 0.4 | 0.4 |
| Air cushion | 1.0 | 0.7 | 1 | 0.7 | 0.9 | 0.7 |
| Telescopic legs | 0.0 | 0.0 | 0 | 0.1 | 1 | 0.0 |
| | 0-1 | 0-1 | #men | 0-1 | 0-1 | 0-1 |

**Weighted, standardized table**

| Principle | Safety | Reliability | Operation | Costs | Engagement time | Calculation time | Score (high=good) |
|---|---|---|---|---|---|---|---|
| Bard I system | 1.6 | 2.7 | 0.5 | 1.8 | 2.8 | 0.8 | **10.2** |
| Rack enclosure | 1.8 | 3.0 | 0.5 | 1.5 | 2.4 | 0.8 | **10.0** |
| Wooden blocks | 1.8 | 2.7 | 0.5 | 1.8 | 2.8 | 0.7 | **10.3** |
| Bard I variant | 1.6 | 2.4 | 0.5 | 1.2 | 2.4 | 0.8 | **8.9** |
| Double wedge | 1.6 | 3.0 | 1.0 | 2.4 | 4.0 | 0.5 | **12.5** |
| Inside clamping | 1.2 | 2.4 | 0.5 | 1.2 | 1.6 | 0.4 | **7.3** |
| Cable jacking system | 1.6 | 1.5 | 0.3 | 2.7 | 1.6 | 0.5 | **8.2** |
| Leg clamp (hardware store variant) | 1.8 | 2.7 | 0.5 | 1.5 | 2.8 | 0.7 | **10.0** |
| Leg clamp (naval-technology variant) | 1.4 | 1.5 | 0.3 | 1.5 | 1.6 | 0.4 | **6.7** |
| Electro magnet | 1.0 | 1.2 | 0.5 | 1.2 | 3.6 | 0.9 | **8.4** |
| Tunneling variant | 1.2 | 1.5 | 0.3 | 1.2 | 1.6 | 0.5 | **6.3** |
| Band clamping | 1.6 | 1.8 | 0.3 | 2.7 | 2.8 | 0.8 | **10.0** |
| Supporting | 1.0 | 1.2 | 0.3 | 2.4 | 1.6 | 0.5 | **7.0** |
| Leg trap | 1.4 | 3.0 | 1.0 | 2.4 | 4.0 | 0.7 | **12.5** |
| Wrench | 0.6 | 0.9 | 0.5 | 1.5 | 1.6 | 0.4 | **5.5** |
| Air cushion | 2.0 | 2.1 | 0.5 | 2.1 | 3.6 | 0.7 | **11.0** |
| Telescopic legs | 0.0 | 0.0 | 1.0 | 0.3 | 4.0 | 0.0 | **5.3** |
| | **2** | **3** | **1** | **3** | **4** | **1** | **14.0** |

Table 14: MCA principles

The left table shows the values given; the table at the right is the weighted and standardized values, with the last column the final score. The upper line shows the values which would be taken for the Bard I system. The green values are the options chosen for further elaboration. This choice is made according to all values above the score of 9. This choice is made because the system should be at least as good as Bard I, but the values in the table above are not quite exact, so a range around Bard I has been taken of two points (which is about 20% of the Bard I score). The table and all the numbers are explained in the next section.

### 11.10.3 Explanation of the MCA:

#### 11.10.3.1 Criteria

The Multi Criteria Analysis conducted to chose between the principles consists of the following criteria and ranges, due to the estimations most criteria are taken between zero and one to give an outline.

| **Criterion** | **Value** | **Explanation** |
|---|---|---|
| **Safety** | 0 | Failure of one small part causes major damage or the change is very large |
| | 1 | System has no safety hazard |
| **Reliability** | 0 | System tends to have lots of problems and is not reliable |
| | 1 | System is unable to fail |
| **Operation** | # persons | Number of persons involved in the operation of the system for one leg |
| **Costs** | 0 | System is very expensive |
| | 1 | System has no additional costs |
| **Engagement time** | 0 | Time consuming |
| | 1 | No extra time needed for calculation |
| **Calculation time** | 0 | Extreme difficult structure takes a lot of calculation time |
| | 1 | No extra calculation time needed |

#### 11.10.3.2 Weight factors

The final table was weighted according to the next weight factors:

| Criterion | Weight | Explanation |
|---|---|---|
| Safety | 2 | Safety is important but should be considered during calculation |
| Reliability | 3 | Reliability weighs heavier, problems might arise |
| Operation | 1 | Important to operational costs, but other factors are more important |
| Costs | 3 | Are important, but not leading, other factors are more important |
| Engagement time | 4 | Most important factor, major target of thesis |
| Calculation time | 1 | Least important factor, makes the design easier, not important to system |

#### 11.10.3.3 Scores

In order to explain the numbers given in the left table of Table 14, another table was constructed to explain the basic considerations about the criteria. These considerations are shown in Table 15: MCA principles: considerations

| Principle | Safety | Reliability | Operation | Costs | Engagement time | Calculation time |
|---|---|---|---|---|---|---|
| Bard I system | Moving parts, concentrated force | Loosing a cylinder continues force | Acc to CJ | 8 cylinders | Acc to CJ | Pushing |
| Rack enclosure | Moving parts, no structural damage | No out bending leg, compared with Bard I | Acc to CJ | 16 cylinders | Acc to CJ | Pushing |
| Wooden blocks | " | When engaged safe, block inside | Acc to CJ | 16 cylinders | fastener than CJ-variant, less cylinders | Swinging in, difficult with shear |
| Bard I variant | Moving parts, concentrated force | Loose one rack, zero left, easy engage | Acc to CJ | 4 cylinders | according to bard I | Pushing |
| Double wedge | With to much force damage to guides | No moving parts | Jacking ensures fastening | Only wedges | Jacking ensures fastening | More difficult due to angled forces |
| Inside clamping | Rack-hull separation | Losing one rack, remains the opposite | Acc to CJ | 8 cylinders | Acc to CJ | Difficult between rack-hull |
| Cable jacking system | Slicing cable | Losing one cable gives torsion | Cable has to be attached | Only cables and attachments | " | Effects on jacking system |
| Leg clamp (hardware store variant) | Moving parts, no structural damage | Losing clamp side | Acc to CJ | Large metal piece to move | " | Pushing |
| Leg clamp (naval-technology variant) | Small pins, shear damage | Losing one side, torsion | Alignment needed | Difficult clamps | " | more difficult, concentrated stress, shear |
| Electro magnet | Large magnetic field | Loosing or disturbed field | One push to activate | Expensive magnets | Only building of mag. Field | Attracting |
| Tunneling variant | Misalignment causing damage to legs | loosing beam | Difficult alignment | 4 cylinders + adapted leg | Long distance, difficult aiming | Filling, arrangement of leg get diff. |
| Band clamping | Slicing band | loosing band tension | Band attachment/ alignment | Only band + winch | Strapping | Attracting |
| Supporting | Structural failure, LSFS heavy damaged | Large moving part, detachable | Has to be attached | Very strong/ stiff structure + attachments | Has to be attached | joints will get difficult |
| Leg trap | Shearing causing damage to trap | No moving parts | Jacking ensures fastening | Only structural widening | Jacking ensures fastening | Danger from extra shear |
| Wrench | Damage to legs or J-house due to wrench | Losing power = loosing tension | Acc to CJ | Large metal piece to move | Acc. To CJ | Forecasting effects from wrenching diff. |
| Air cushion | no | Losing one side no one left | One push to activate | Cushions + air pumps | Inflation | Inflating, force distribution diff. |
| Telescopic legs | Major hazzard when telescopic system fails | Jacking could be problem, moving parts below water | Jacking ensures fastening | Expensive legs | Jacking ensures fastening | Difficult leg structure |
| **Range** | **0-1** | **0-1** | **# persons** | **0-1** | **minutes** | **0-1** |

Table 15: MCA principles: considerations

## 11.11 ELABORATION OF PRINCIPLES, RACK ENCLOSURE BAR DIMENSIONING

Dificulty of the rack enclosure variant could be the necessary height of the bars combined with the available space. When referring to Bard I the thickness of the racks of the leg will be 75mm, the distance to the hull of the leg will then also be 75mm. The gap between guides and racks will be a maximum of 30mm. This means the pushing area is limited to 75mm but the bar needs to be at least 105mm (75 + 30) width. The maximum width of the bars could be 150[37] mm. So this would be possible.

When referring to Mannesmann Rexroth (n.d.) the maximum force which can be applied by a piston of 320 mm diameter is 2574kN. The force exposed to the upper guide at Bard I will be around 8500kN[38]. Taking into account a safety factor of 1.2 the force would be:

$F_{ref} = F * \gamma = 8500*1.2 = 10200kN$
$F_{bar} = F_{ref} / 2 = 5100kN$
$F_{cylinder} = F_{bar} / 2 = 2550kN$

This would imply two cylinders per bar, and sixteen in total (two bars per rack, four racks). The diameter of the piston rod would be 180mm; this means a minimal dimension of the bars of 360*105 mm. The pushing force would be[39] 188N/mm$^2$ which is much lower than the yield stress of S355 steel: 355N/mm$^2$.

All combined it would be possible to use this bars and cylinders in a reasonable way.

[37] $b_{bar} = l_{gap}+l_{rack} = 75+75mm$
[38] Roughly the roll summed with the pitch motion loads gather during force analysis, section 11.2.
[39] $\sigma_{push} = F/(l*b)=5.1E6/(360*75);$ 75 mm is the effective pushing width.

## 11.12 ELABORATED PRINCIPLES, WOODEN BLOCK, FORCES

In order to get insights in some forces arising from the wooden block variant the schematization from Figure 54 was used with the formulas below.

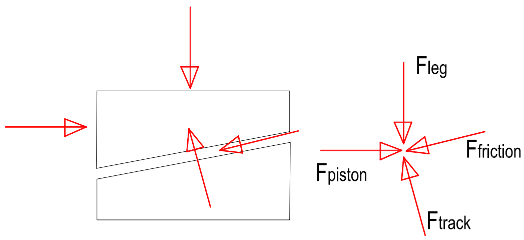



Figure 54: Mechanical scheme wooden block

$F_{leg}$ = 5900 *1.2 = 7800 kN (max. pitch force upper guide * safety factor)
$F_{friction}$ = 0.1 * $F_{track}$ e.g. α = 10: $F_{friction}$= 720 kN (0.1 = coeff. of friction steel-steel)
$F_{track}$ = $F_{leg}$ / cos(α) e.g. α = 10: $F_{track}$ = 7200kN
$F_{legpiston}$ = tan(α )* $F_{leg}$ e.g. α = 10: $F_{legpiston}$= 1375 kN
($F_{legpiston}$ = horizontal element from leg force (split in track force and leg piston force))

All combined $F_{piston}$ would be approximately 1375 + 720 = 2095 kN to engage the system at maximum stress level.
When pulling out the wedges the friction coefficient could raise until 1.0 this would cause the piston force to be:

$F_{leg}$ = 5900 *1.2 = 7800 kN (max. pitch force upper guide * safety factor)
$F_{friction}$ = 1.0 * $F_{track}$ e.g. α = 10: $F_{friction}$= 7200 kN (1.0 = coeff. of friction steel-steel)
$F_{track}$ = $F_{leg}$ / cos(α) e.g. α = 10: $F_{track}$ = 7200kN
$F_{legpiston}$ = tan(α )* $F_{leg}$ e.g. α = 10: $F_{legpiston}$= 1375 kN

All combined $F_{piston}$ would be approximately 1375 + 7200 = 8575 kN to disengage the system at maximum stress level.

## 11.13 ELABORATED PRINCIPLES, DOUBLE WEDGE, DISPLACEMENT AND INCLINATION

When referring to Bard I with $L_{abjah}$ = 50.4m, the displacement between the upper and lower guides and the angle at the upper guide in field pitch will be according to the next formulas:

Displacement:

1th order: $w_0 = \frac{1 \cdot M \cdot l^2}{16 \cdot E \cdot I} = \frac{1 \cdot 6.33E4 \cdot 14.1^2}{16 \cdot 2.1E8 \cdot 1.67} = 0.0022(m)$

2nd order: $w_1 = \frac{1 \cdot (w_0 \cdot F_v) \cdot l^2}{16 \cdot E \cdot I} = \frac{1 \cdot (0.0022 \cdot 3.95E3) \cdot 14.1^2}{16 \cdot 2.1E8 \cdot 1.67} = 3.4E - 7(m)$

Total: $w = w_0 + w_1 = 0.0022(m) = 2.2mm$

Angle:

1th order: $\varphi_0 = \frac{1 \cdot M \cdot l}{3 \cdot E \cdot I} = \frac{1 \cdot 6.33E4 \cdot 14.1}{3 \cdot 2.1E8 \cdot 1.67} = 8.48E - 4(rad)$

2nd order: $\varphi_1 = \frac{1 \cdot (w_0 \cdot F_v) \cdot l}{3 \cdot E \cdot I} = \frac{1 \cdot (0.0022 \cdot 3.95E3) \cdot 14.1}{3 \cdot 2.1E8 \cdot 1.67} = 1.16E - 7(rad)$

Total: $\varphi = \varphi_0 + \varphi_1 = 8.48E - 4(rad) = 0.05°$

This means when calculating for two fixation point analysis the maximum angle at upper guide level to one side will be 0.05 degrees, so the maximum angle to calculate with will be 0.1 degrees (with no safety factor taken into account). This means when referring to the design of the wedges the contact area has to be able to deform at least 0.1 degrees under condition of the environmental forces without failing or the shapes needs to be able to overcome this angle. When also deformation of the wedges and constructional margins are taken into account this value could increase further more. Also the inclination of the legs has to be counted for when engaging the system. At top the distance between the leg and the guides would be maximum 30 mm. This means the angle of inclination would be tan(30/14000) = 3.73E-5 degree. Due to the small angle it is quite reasonable to continue calculating with 0.1 degrees.

## 11.14 ELABORATED PRINCIPLES, DOUBLE WEDGE, WEDGE ANGLE

To get the wedges stick together when the weight of the roller wedge and the friction of the roller are not taken into account, the friction force between the two wedges needs to be larger than the force which drives the roller wedge upwards away from the leg wedge. In this case the angle is calculated conservative but it can be reasonable to add a safety coefficient *γ*. The used signs can be acquired from Figure 55.

$$\frac{F_v}{\cos(\alpha)} < \gamma \cdot F_w = \gamma \cdot N \cdot c_w = \gamma \cdot \frac{F_p}{\cos(\alpha)} \cdot c_w$$

$$\frac{F_p \cdot \tan(\alpha)}{\cos(\alpha)} < \gamma \cdot \frac{F_p}{\cos(\alpha)} \cdot c_w$$

$$\tan(\alpha) < \gamma \cdot c_w$$

$$\alpha < tan^{-1}(\gamma \cdot c_w)$$

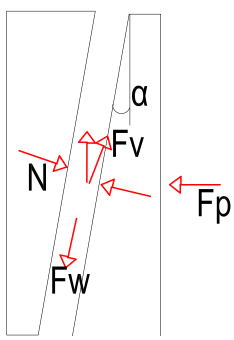



Figure 55: Wedge angle calculation signs

For some combinations of safety coefficients and friction coefficients the maximum allowable wedge angle is given in Table 16. It has to be considered the formula is only valid if a force $F_p$ is applied.

Maximum angle

| γ\Cw | 0.1 | 0.5 | 0.8 | 1 | 1.2 |
|---|---|---|---|---|---|
| 1 | 5.710593 | 26.56505 | 38.65981 | 45 | 50.19443 |
| 1.2 | 6.842773 | 30.96376 | 43.83086 | 50.19443 | 55.22217 |
| 1.5 | 8.530766 | 36.8699 | 50.19443 | 56.30993 | 60.9454 |

Table 16: Maximum allowable wedge angle

## 11.15 ELABORATED PRINCIPLES, BAND CLAMPING, BENDING DIAMETER

The diameter of the rope proposed of 102 mm from Vrijhof Anchors (2006), needs a minimum rope diameter according to the next formulas. The first formula is for failure of the strains and the second is for failure of the sheeting.

$$D = \frac{4 * W}{\pi * \sigma_b * \{d * 0.15 * t\}^{0.5}} = \frac{4 * 1E7}{\pi * \left\{\frac{1E7}{\pi * 51^2}\right\} * \{102 * 0.15 * 11\}^{0.5}} = 801mm$$

Or

$$D > 24 * (d - 2 * t) = 24 * (102 - 2 * 11) = 1920mm$$

In which:

| | | |
|---|---|---|
| *D* | = | Minimum bending diameter mm |
| *W* | = | Line load N |
| *d* | = | Sheathed cable diameter mm |
| *t* | = | Sheathing radial thickness mm |
| $\sigma_b$ | = | Maximum bearing pressure N/mm2 |

This would mean a minimum radius of 1920/2=960 mm.

## 11.16 ELABORATED PRINCIPLES, FEATURE DESCRIPTIONS

*In order to draw conclusions about the principle taken for elaboration some features about the elaborated principles were established. The features are listed in Table 17 explanations are given aft.*

| | Pitfall | Calculation leg | Calculation guide/ Jacking house | Calculation System | Engagement (s) | Reliability | Ocean transit |
|---|---|---|---|---|---|---|---|
| Bard I | 2 | 4 | 3 | 3.5 | 30 | 7 | 2 |
| Rack enclosure | 2 | 4 | 3 | 3 | 30 | 6 | 2 |
| Wooden block variant | 2 | 4 | 2 | 2 | 81 | 9 | 2 |
| Double wedge | 2 | 2 | 3 | 2 | 0 | 9 | 2 |
| Leg clamp | 2 | 4 | 2 | 1 | 50 | 9 | 2 |
| Band clamping | 2 | 3 | 3 | 3 | 24 | 7 | 2 |
| Leg trap | 2 | 2 | 3 | 2 | 0 | 7 | 2 |
| Air cushion | 2 | 4 | 3 | 3 | 56 | 9 | 2 |
| Range | 0-2 | 0-4 | 0-4 | 0-4 | qua | 1_10 | 1_3 |

Table 17: Elaborated principles, unweighted, unstandardized

### 11.16.1 Rack enclosure

Key-elements:

- 16 cylinders with 1 bar per 2 cylinders.
- Jacking house mountings

Calculation time

- Adjustment to the leg: The leg remains the same.
- Adjustment to the Guide structure/ jacking house: minimal, only cylinder mountings.
- Complexity: Only pushing cylinders but synchronizing might get complicated.

Engagement time:

- Speed of one cylinder is about 1.6 mm/s, major distance of 48 mm can be done in 30s.

Reliability:

- 16 cylinders, failure of one would cause extra force in the remaining 3 per side.

Ocean transit

- Ocean towage is possible by means of using more cylinders per bar or using an extra bar when performing ocean transit, but it would imply doubling the system.

### 11.16.2 Wooden blocks

Key elements

- 4 Solid pieces of material
- 4 Cylinders

- 4 "Tracks" (structural change)
- 8 bearings

Calculation time
- Adjustment leg: The legs stay as they are
- Adjustment guides/ jacking house: An extra construction has to be added below or above the guides, but only horizontal forces are arising so major adjustments are not necessary.
- Complexity system: Some more compared with CJ, because of all the bearings and the adjustments to the structure.

Engagement time
- Due to the longer stroke needed (e.g. at 10 degrees, the stroke would be 30mm/ tan(10) = 170mm, combined with the piston speed of 2.1mm/s the engagement time would be 81 seconds.

Reliability
- 4 pushing cylinders, failure of one cylinder causes the fastening system to fail.

Ocean transit
- In order to change the system for ocean transit conditions, the only adjustment would be increasing the size of the system, stronger cylinders and structures. But it is possible by doubling the system.

### 11.16.3 Double wedge

Key elements
- 4 rolled wedges with bearings
- 4 leg wedges
- 4 consoles

Calculation time
- Adjustment leg: The legs need to be adjusted to carry the wedges at the hull.
- Adjustment guides/ jacking house: the roller wedge needs to be supported.
- Complexity system: Complexity arises from the needed friction to ensure the wedges stick to each other, and on the other hand the force needed to undo friction when disengaging.

Engagement time
- Engagement time will be zero because the system is passive.

Reliability
- The system would fail if the jacking system fails (which would be worse than losing sea fastening).

Ocean transit
- In order to change the system for ocean transit conditions, the only adjustment necessary would be increasing the strength of wedges, rollers and mountings.

### 11.16.4 Leg clamp

Key elements
- 2 activators
- 4 wedges
- 2 opposite clampers

Calculation time
- Adjustment leg: The legs stay as they are
- Adjustment guides/ jacking house**:** A heavy construction is needed to guide the wedges

and the activator.

- Complexity system: The elements of the system need to be outlined correct and the system could be very heavy.

Engagement time

- Engagement is done by pushing the yoke of the remaining two jacking cylinder which are not needed in transit, a bit higher. This distance would be about 30mm. This could be done in approximately 40/0.8 = 50 seconds.

Reliability

- When outlined correct the system would be reliable.

Ocean transit

- In order to change the system for ocean transit conditions, the only adjustment necessary would be increasing the sizes of the system, e.g. stronger activator and wedges.

### 11.16.5 Band clamping

Key elements

- 1 band
- 2 guiding shoes
- 2 engagement guides
- 1 or 2 driving systems

Calculation time

- Adjustment leg: The legs remain as they were, because the force is spread evenly along the racks.
- Adjustment guides/ jacking house: Depends on the arrangement of the driving system. Worst case would be mounting the driving systems.
- Complexity system: Design of the leg shoes and choice of the belt would be difficult.

Engagement time

- Engagement time also depends on which arrangement to take. When making use of systems already available on deck or even interconnecting the legs, the engagement would take longer than making use of extra driving systems. Driving length would only be the 30 mm between the racks and the guides (= 48 mm at this angle) and some stretch of the band. For the multi criteria analysis extra driving systems are taken. The force of 10 MN can be transported by two 450mm pistons with a speed of 1.0mm/s. When pulling at 2 sides the engagement would take 24 seconds (2mm/s).

Reliability

- Reliability of this alternative comes from the few driving systems needed for engagement. Unreliability might arise from failure of the band, but this could be well chosen.
- Ocean transit
- To be able to use the system with ocean transit conditions only increasing the capability of the band and the pulling system is needed, thus doubling the system.

Ocean transit

- In order to change the system for ocean transit conditions, the only adjustment necessary would be doubling the sizes of the system.

### 11.16.6 Leg trap

Key elements

- 4 leg guiders/ activators and 4 hull activators

- 4 consoles

Calculation time

- Adjustment leg: The spudcan section should be strengthened to allow these forces.
- Adjustment guides/ jacking house: The consoles should be designed for higher forces to ensure the continuous pressure from the fastening can be applied.
- Complexity system: The alignment of the movements will be difficult, mayor difficulty could be with normal wear and tear the alignment can get disturbed.

Engagement time

- Because the system is passive engagement takes no extra time.

Reliability

- Unreliability of this system comes from wear and tear at all contact surfaces, with loss of alignment and pretension accordingly.

Ocean transit

- To be able to use the system in ocean transit only increasing the capability of the consoles is needed.

#### 11.16.7 Air cushion

Key elements

- At least 4 pancake cylinders
- Jacking house mountings.

Calculation time

- Adjustment leg: The leg stays as it is.
- Adjustments guides/ jacking house: The cylinders have to be mounted.
- Complexity system: The design of the cylinders could be difficult.

Engagement time

- Engagement of the system is done by extending the cylinder. The speed of this cylinder type is not determined yet but would be less than 0.8mm/s, so the engagement time will be more than 30/0.8 = 37.5s. So for comparison 1.5 times 37.5 = 56.25seconds is taken.

Reliability

- Losing one cylinder causes the system to fail; through its simplicity the system could be reliable.

Ocean transit

- Doubling the amount of cylinders, or increasing cylinder size would ensure ocean transit fastening.

## 11.17 DETAIL, WEDGE CALCULATIONS

Dynamic drive in and static (with $c_{w2}$ = 0). Care has to be taken that the normal forces cannot be negative (if-functions within MS Excel).

$$F_p = (1.1 * (F_{ug}/(\cos(\alpha) - \sin(\alpha) * c_{w2}) * (\cos(\alpha) * c_{w2} + \sin(\alpha))))$$
$$F_{n2} = (F_p + F_{ug} * c_{w1})/(\cos(\alpha) * c_{w1} - \sin(\alpha) * c_{w2} * c_{w1} + \cos(\alpha) * c_{w2} + \sin(\alpha)$$
$$F_v = -F_{n3} * c_{w3} + F_{n2} * c_{w2} * \cos(\alpha) + F_{n2} * \sin(\alpha)$$
$$F_{n1} = F_{n2} * (\cos(\alpha) - \sin(\alpha) * c_{w2}) - F_{ug}$$
$$F_{n3} = -F_{n2} * c_{w2} * \sin(\alpha) + \cos(\alpha) * F_{n2}$$

Dynamic pull out, care has to be taken that for calculation reasons $F_{n1}$ has been taken as zero. When $F_{ug}$ is faced in the opposite direction, the pull force should be $F_{ug}$ * $c_{w1}$. Also the support force should not be higher than zero, because the leg would than certainly break loose.

$$F_p = -F_{ug}/(\cos(\alpha) + \sin(\alpha) * c_{w2}) * ((\cos(\alpha) - E50 * c_{w2})$$
$$F_v = -F_p + F_{ug} * c_{w3}$$

## 11.18 DETAIL, PRETENSION BOLTS, DIMENSIONING

The feasibility of the pretension bolt system is based on the amount of bolts necessary and the corresponding necessary wedge height.

When assuming the connection made of M20 bolts (quality 8.8) with a distance of 100mm center-to-center and a maximum width of the wedge of 1000mm combined with a maximum pretension of such bolts of 105kN according to www.tribologie.nl, this implies a minimum amount of bolts of:

$$F_{bolt} = \frac{F_{vmax}}{c_{w3}} = \frac{0.77\text{E}6}{0.1} = 7.7\text{MN}$$

$$n_{bolt} = \frac{F_{bolt}}{\left(\frac{F_{pretension\ bolt}}{\gamma}\right)} = \frac{7.7E6}{\frac{105E3}{1.5}} = 110pcs$$

The minimum distance between the bolts of $d_{bolt}$ = 100 mm combined with a minimum distance to the sides of half this distance would lead to a minimum wedge height of:

$$h_w = n_{vertical} * d_{bolt} = \{3 + [(n_{bolt} - n_{bolt\ horizontal})/2]\} * d_{bolt}$$

$$h_w = \left\{3 + \left[\left(n_{bolt} - \frac{2*w_{wedge} - d_{bolt}}{d_{bolt}}\right)/2\right]\right\} * d_{bolt} = \left\{3 + \left[\left(110 - 2 * \frac{1000-100}{100}\right)/2\right]\right\} * 100 = 4900mm$$

This is far too much to make it possible; it could however be smaller when taking more complete bolt rows, e.g. 13 rows with a corresponding height of around 320mm. Another problem remains: such amount of bolts would be difficult to adjust every time. Also it would be hard to reach these bolts.

## 11.19 DETAIL, SPRING CHARACTERISTICS

| **Calculator for round wire helical springs (ref: www.tribology-abc.com)** | | |
|---|---|---|
| Diameter of spring wire d | 75 | $10^{-3}$ m |
| Mean coil diameter D | 300 | $10^{-3}$ m |
| Number of active coils n | 9 | - |
| Shear modulus G = E / ( 2 ( 1+v ) ) | 79.3 | $10^{9}$ Pa |
| Spring force F | 266666 | N |
| | | |
| Spring outer diameter Dout = D + d | 375 | $10^{-3}$ m |
| Spring radius r = D / 2 | 150 | $10^{-3}$ m |
| Spring length closed (solid) Lc = n d | 675 | $10^{-3}$ m |
| Spring deflection f | 206.61 | $10^{-3}$ m |
| Spring stiffness k = dF / df = F / f | 1290.6 | $10^{3}$ N/m |
| Spring length free L0 > Lc + f | 881.61 | $10^{3}$ N/m |
| Pitch of lead s = L0 / n | 97.96 | $10^{-3}$ m |
| Shear stress τ | 482.89 | $10^{6}$ Pa |

Table 18: Spring characteristics

## 11.20 DETAIL, MASS CALCULATION BOLT SPACER

Total mass of the bolt spacer adjustable connection can be divided into the bolts self, the necessary extra width of the wedge, the console for disengagement, the impact strip and the structure needed to connect the bolts to.

**Bolts:**
6 pieces 0.12 meter M20 bolts (8.8 quality)
$m_{bolts} = 6*l*\pi*r^2*\rho = 6* 0.12 * \pi*0.01^2*7850 = 1.8\ kg$

**Extra width wedge:**
Extra width was taken as 0.02 meter (assumption of double bolt size), increasing the available area for the bolts.
1 meter width, wedge height 0.2meter
$m_{width} = l*b*h*\rho = 1.0*0.02*0.2 *7850 = 31.4kg$

**Console:**
For calculation assumed to have a 45 degree angle:
1 meter, 0.04 meter wedge width:
$m_{console} = l*0.5*h*b*\rho = 1.0*0.5*0.04*0.04*7850 = 6.3kg$

**Impact strip:**
Height of strip is taken width a force distribution through the strip over 45 degrees, so it would be: $((l_{wedge}-d_{bolts}*n_{bolts})/n_{bolts})/2 = (1000-20*6)/6)/2 = 73{,}3mm$
Length of 1 meter, width of 0.04 meter and a height of 0.074.
$m_{impact} = l*h*b*\rho = 1.0*0.074*0.04*7850 = 23.2kg$

**Connection strip:**
Lengths of 1 meter, 0.015 meter tread height, width of 0.04meters.
$m_{conn.} = L*h*b*\rho = 1.0*0.015*0.04*7850 = 4.7kg.$

**Total:**
$m_{adj.conn.} = m_{bolts} + m_{width} + m_{console} + m_{impact} + m_{conn.} = 1.8 + 31.4 + 6.3 + 23 + 4.7 = 67.4kg$

## 11.21 DETAIL, FRAMEWORK HULL STIFFENER CHECK DATA

This data was gathered with use of Framework 2D version 9.41.

Version: 9.41
Date is: 8/4/2008 9:30:59 AM

****** D A T A  I N P U T ******

**** N O D A L  I N P U T ****

| Node no. | X-coordinate [m] | Y-coordinate [m] |
|---|---|---|
| 1 | 0.000E+00 | 0.000E+00 |
| 2 | 1.750E+00 | 0.000E+00 |
| 3 | 3.500E+00 | 0.000E+00 |
| 4 | 0.000E+00 | 1.875E+00 |
| 5 | 0.000E+00 | 3.750E+00 |
| 6 | 3.500E+00 | 1.875E+00 |
| 7 | 3.500E+00 | 3.750E+00 |

**** B E A M  I N P U T ****

| Beam no. | Start node | End node | E-modulus [kN/m2] | Spec.mass [kg/m3] | Area [m2] | Moment of inertia [m4] |
|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 2.100E+08 | 0.000 | 2.350E-02 | 7.223E-03 |
| 2 | 2 | 3 | 2.100E+08 | 0.000 | 2.350E-02 | 7.223E-03 |
| 3 | 3 | 6 | 2.100E+08 | 0.000 | 1.980E-02 | 8.700E-04 |
| 4 | 6 | 7 | 2.100E+08 | 0.000 | 1.980E-02 | 8.700E-04 |
| 5 | 1 | 4 | 2.100E+08 | 0.000 | 1.980E-02 | 8.700E-04 |
| 6 | 4 | 5 | 2.100E+08 | 0.000 | 1.980E-02 | 8.700E-04 |

****** L O A D S *******

**Base loadcase number 1**

**** B L O C K  L O A D S ****

| Beam no. | Startnode | Startblock [m] | Endblock [m] | Blockangle(X-axis) [degrees] | "Q1" [kN/m] | "Q2" [kN/m] | Gl/Loc [G/L] |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1.250 | 1.750 | 90.00 | 4200.000 | 4200.000 | G |
| 2 | 2 | 0.000 | 0.500 | 90.00 | 4200.000 | 4200.000 | G |

****** O U T P U T calculation results (base) ******

## Base loadcase no. 1

### ** Nodal displacements with respect to the global system of axes **

| Node no. | Ux [m] | Uy [m] | fi [degrees] |
|---|---|---|---|
| 1 | 4.596E-05 | 1.894E-03 | 9.666E-02 |
| 2 | 6.440E-18 | 3.945E-03 | 4.389E-16 |
| 3 | -4.596E-05 | 1.894E-03 | -9.666E-02 |
| 4 | -7.678E-04 | 9.470E-04 | -2.311E-02 |
| 5 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 6 | 7.678E-04 | 9.470E-04 | 2.311E-02 |
| 7 | 0.000E+00 | 0.000E+00 | 0.000E+00 |

### ** Beam actions with respect to the local system of axes **

| Beam no. | Node no. | Normal force [kN] | Shear force [kN] | Moment [kN.m] |
|---|---|---|---|---|
| 1 | 1 | 1.296E+02 | -2.100E+03 | -3.252E+02 |
| | 2 | -1.296E+02 compr. | 2.100E-04 | -2.825E+03 |
| 2 | 2 | 1.296E+02 | -2.100E-04 | 2.825E+03 |
| | 3 | -1.296E+02 compr. | -2.100E+03 | 3.252E+02 |
| 3 | 3 | 2.100E+03 | -1.296E+02 | -3.252E+02 |
| | 6 | -2.100E+03 compr. | 1.296E+02 | 8.220E+01 |
| 4 | 6 | 2.100E+03 | -1.296E+02 | -8.220E+01 |
| | 7 | -2.100E+03 compr. | 1.296E+02 | -1.608E+02 |
| 5 | 1 | 2.100E+03 | 1.296E+02 | 3.252E+02 |
| | 4 | -2.100E+03 compr. | -1.296E+02 | -8.220E+01 |
| 6 | 4 | 2.100E+03 | 1.296E+02 | 8.220E+01 |
| | 5 | -2.100E+03 compr. | -1.296E+02 | 1.608E+02 |

### ** Support forces of the nodes with prescribed deformations (Global) **

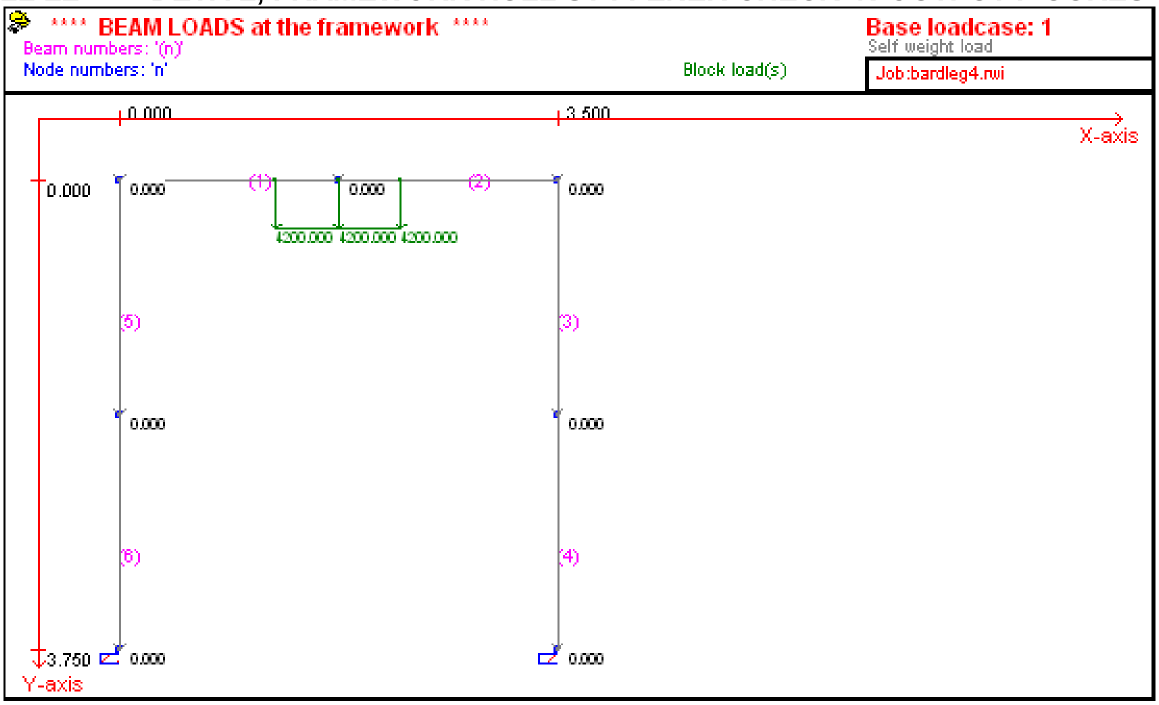
| Node no. | Fx [kN] | Fy [kN] | M [kN.m] |
|---|---|---|---|
| 5 | 1.296E+02 | -2.100E+03 | 1.608E+02 |
| 7 | -1.296E+02 | -2.100E+03 | -1.608E+02 |

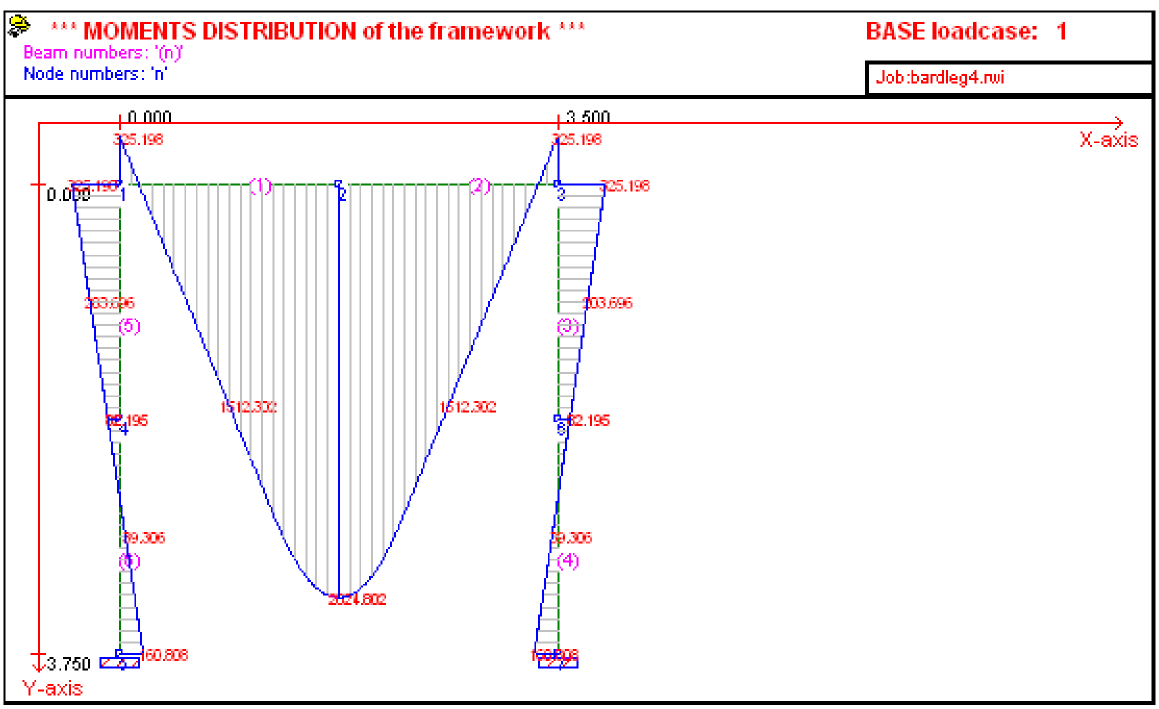
### ** Equilibrium check nodal forces (incl. prescribed nodal forces) **

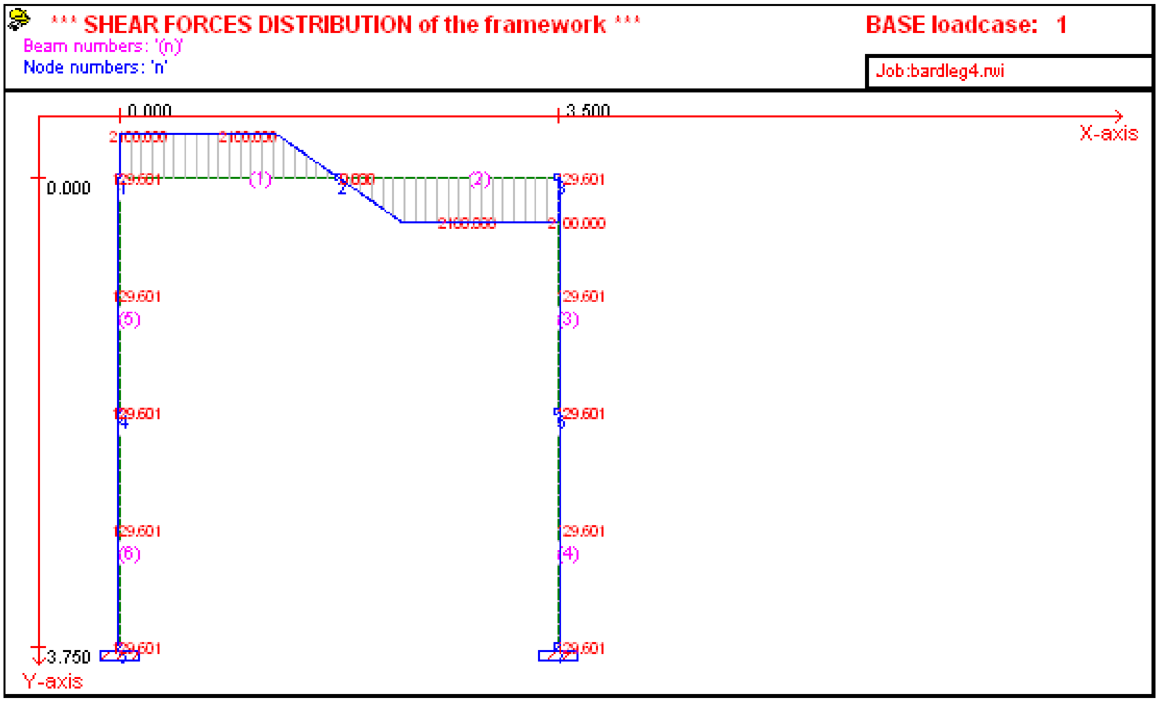
| Node no. | Sum-Fx [kN] | Sum-Fy [kN] | Sum-M [kN.m] |
|---|---|---|---|
| 1 | -2.842E-14 | -9.095E-13 | 1.137E-13 |
| 2 | 2.842E-14 | 2.740E-12 | 3.183E-12 |
| 3 | 5.684E-14 | -2.274E-12 | 5.116E-13 |
| 4 | 5.684E-14 | 0.000E+00 | 1.421E-14 |
| 5 | 1.296E+02 | -2.100E+03 | 1.608E+02 |
| 6 | 0.000E+00 | 0.000E+00 | -4.263E-14 |
| 7 | -1.296E+02 | -2.100E+03 | -1.608E+02 |

****End of the calculation**

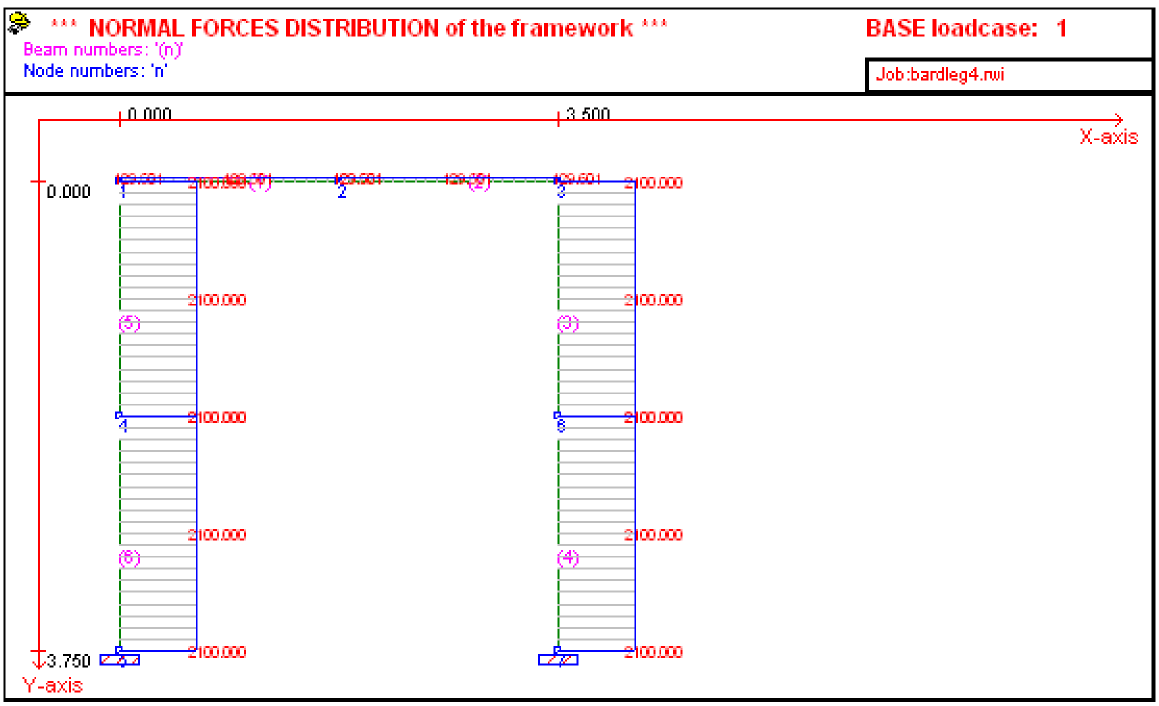
## 11.22 DETAIL, FRAMEWORK HULL STIFFENER CHECK IN-OUTPUT FIGURES





*** SHEAR FORCES DISTRIBUTION of the framework ***
BASE loadcase: 1
Beam numbers: '(n)'
Node numbers: 'n'
Job:bardleg4.rwi
0.000
3.500
X-axis
0.000
-3.750
Y-axis
2100.000
129.601
(1)
(2)
(3)
(4)
(5)
(6)

*** NORMAL FORCES DISTRIBUTION of the framework ***
BASE loadcase: 1
Beam numbers: '(n)'
Node numbers: 'n'
Job:bardleg4.rwi
0.000
3.500
X-axis
0.000
-3.750
Y-axis
2100.000
129.601
(1)
(2)
(3)
(4)
(5)
(6)

## 11.23 DETAIL, FRAMEWORK TRIANGLE STIFFENER CHECK DATA

This data was gathered with use of Framework 2D version 9.41.

Version: 9.41
Date is: 8/4/2008 11:46:55 AM

****** D A T A  I N P U T ******

**** N O D A L  I N P U T ****

| Node no. z | X-coordinate [m] | Y-coordinate [m] |
|---|---|---|
| 1 | 0.000E+00 | 0.000E+00 |
| 2 | 3.500E+00 | 0.000E+00 |
| 3 | 8.750E-01 | 2.000E+00 |
| 4 | 2.625E+00 | 2.000E+00 |
| 5 | 1.750E+00 | 4.000E+00 |

**** B E A M  I N P U T ****

| Beam no. | Start node | End node | E-modulus [kN/m2] | Spec.mass [kg/m3] | Area [m2] | Moment of inertia [m4] |
|---|---|---|---|---|---|---|
| 1 | 1 | 3 | 2.100E+08 | 0.000 | 1.335E-02 | 2.769E-04 |
| 2 | 3 | 5 | 2.100E+08 | 0.000 | 1.335E-02 | 2.769E-04 |
| 3 | 5 | 4 | 2.100E+08 | 0.000 | 1.335E-02 | 2.769E-04 |
| 4 | 4 | 2 | 2.100E+08 | 0.000 | 1.335E-02 | 2.769E-04 |

****** L O A D S *******

**** *N O D A L  L O A D S* ****

| Node no. | F-x [kN] | F-y [kN] | Moment [kN.m] |
|---|---|---|---|
| 5 | | -4160.0000 | |

****** O U T P U T calculation results (base) ******

**Base loadcase no. 1**

**** Nodal displacements with respect to the global system of axes ****

| Node no. | Ux [m] | Uy [m] | fi [degrees] |
|---|---|---|---|
| 1 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 2 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 3 | 9.838E-19 | -1.925E-03 | -3.037E-02 |
| 4 | 1.683E-18 | -1.925E-03 | 3.037E-02 |
| 5 | -3.972E-19 | -3.850E-03 | 1.200E-16 |

## ** Beam actions with respect to the local system of axes **

| Beam no. | Node no. | Normal force [kN] | | Shear force [kN] | Moment [kN.m] |
|---|---|---|---|---|---|
| 1 | 1 | 2.265E+03 | | 1.294E+01 | 2.824E+01 |
| | 3 | -2.265E+03 | compr. | -1.294E+01 | 3.418E-14 |
| 2 | 3 | 2.265E+03 | | 1.294E+01 | -4.024E-14 |
| | 5 | -2.265E+03 | compr. | -1.294E+01 | 2.824E+01 |
| 3 | 5 | 2.265E+03 | | -1.294E+01 | -2.824E+01 |
| | 4 | -2.265E+03 | compr. | 1.294E+01 | -4.042E-14 |
| 4 | 4 | 2.265E+03 | | -1.294E+01 | 1.443E-13 |
| | 2 | -2.265E+03 | compr. | 1.294E+01 | -2.824E+01 |

## ** Support forces of the nodes with prescribed deformations (Global) **

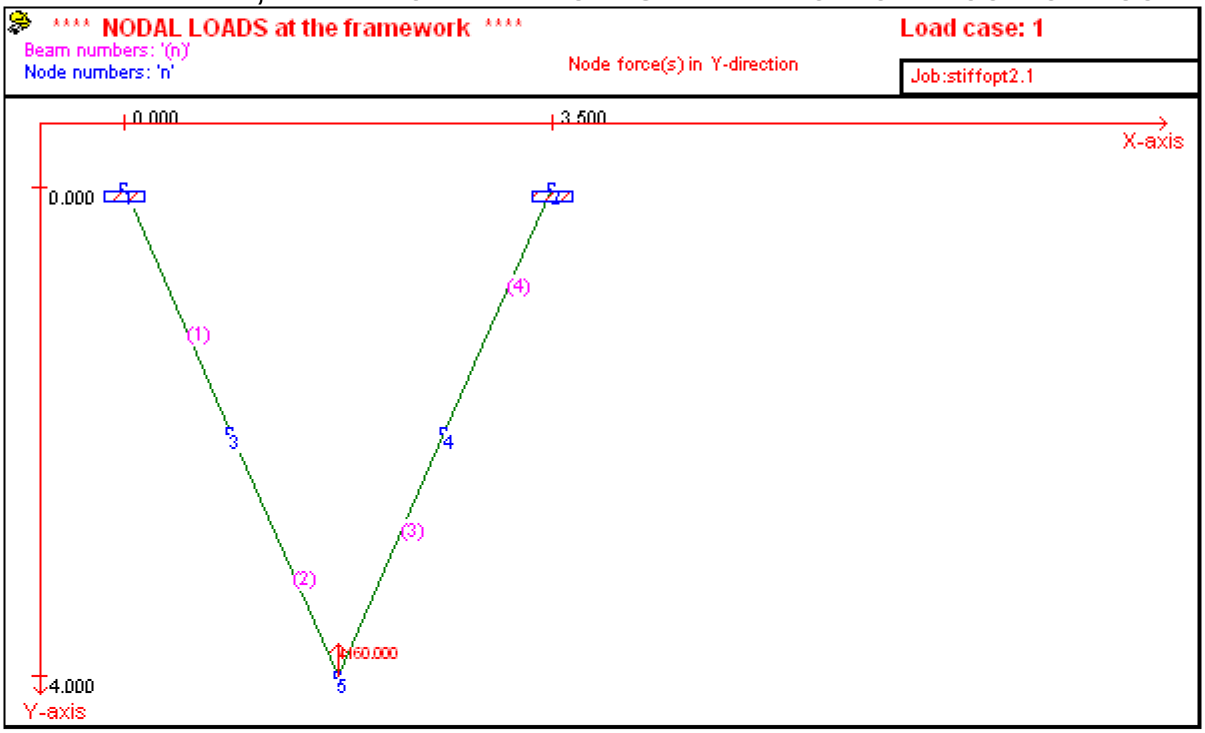
| Node no. | Fx [kN] | Fy [kN] | M [kN.m] |
|---|---|---|---|
| 1 | 8.959E+02 | 2.080E+03 | 2.824E+01 |
| 2 | -8.959E+02 | 2.080E+03 | -2.824E+01 |

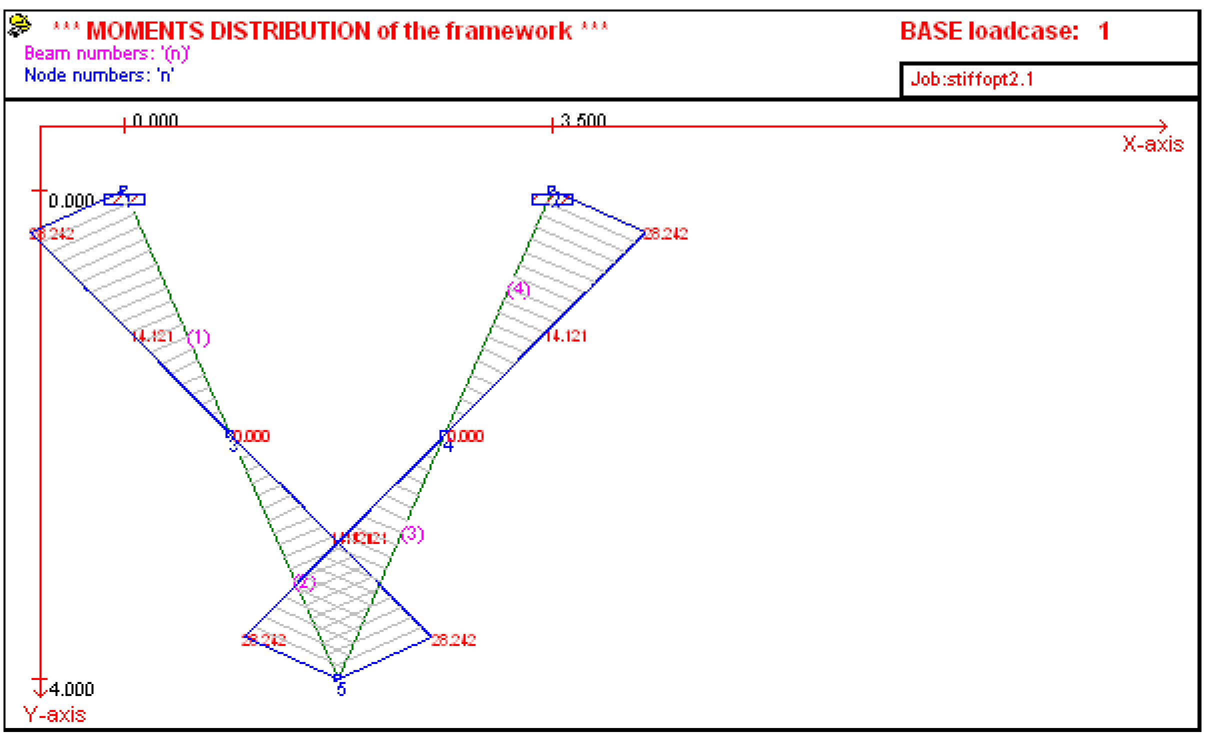
## ** Equilibrium check nodal forces (incl. prescribed nodal forces) **

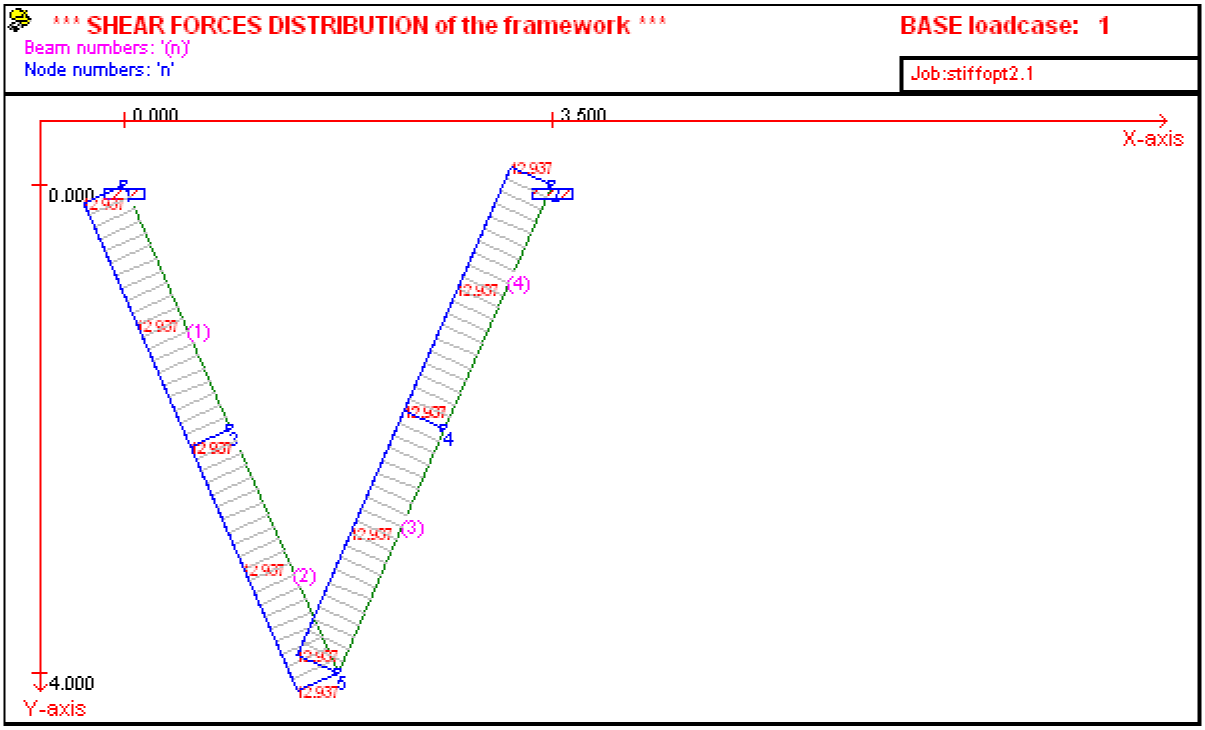
| Node no. | Sum-Fx [kN] | Sum-Fy [kN] | Sum-M [kN.m] |
|---|---|---|---|
| 1 | 8.959E+02 | 2.080E+03 | 2.824E+01 |
| 2 | -8.959E+02 | 2.080E+03 | -2.824E+01 |
| 3 | 2.274E-13 | -4.547E-13 | -6.051E-15 |
| 4 | -1.137E-13 | 0.000E+00 | 1.039E-13 |
| 5 | 0.000E+00 | 0.000E+00 | 1.705E-13 |

## **End of the calculation

## 11.24 DETAIL, FRAMEWORK TRIANGLE STIFFENER CHECK IN-OUTPUT FIGURES




*** SHEAR FORCES DISTRIBUTION of the framework ***
BASE loadcase: 1
Beam numbers: '(n)'
Node numbers: 'n'
Job:stiffopt2.1
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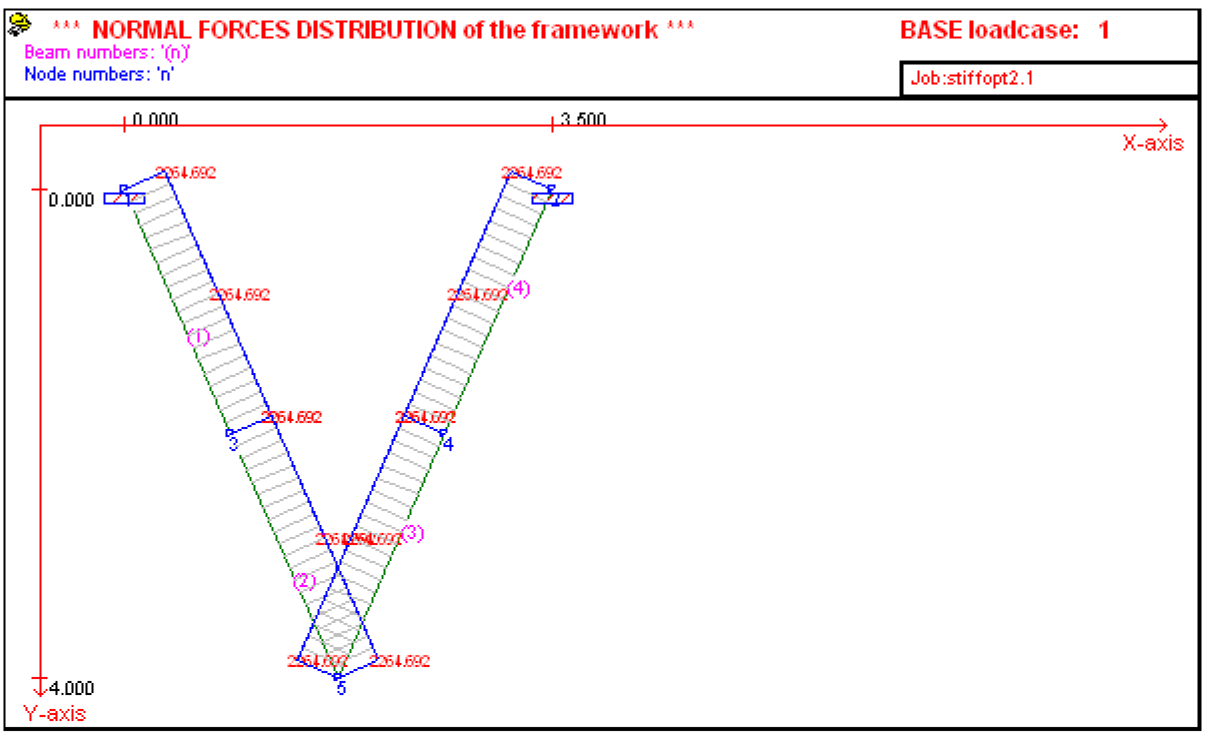
3.500
X-axis
0.000
4.000
Y-axis
12.937
(1)
(2)
(3)
(4)
3
4
5


*** NORMAL FORCES DISTRIBUTION of the framework ***
BASE loadcase: 1
Beam numbers: '(n)'
Node numbers: 'n'
Job:stiffopt2.1
0.000
3.500
X-axis
0.000
4.000
Y-axis
2264.692
(1)
(2)
(3)
(4)
3
4
5

# A standstill to get further

## Leg sea-fastening system for frequently used jack-ups

S. Attema (2008)

University Twente (Enschede, The Netherlands)
GustoMSC (Schiedam, The Netherlands)