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WETFEET

Deliverable 3.7
Engineering of structural membrane for large scale deployment for Symphony

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Report on the engineering of structural membrane (challenges, design and operation) for large scale deployment for Symphony			
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3.0 - Final version	April 2018 Final version

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EXECUTIVE SUMMARY

This report presents Deliverable 3.7 of the WETFEET H2020 project – Report with Engineering of structural membrane for large scale deployment. This report contains the technical details of the structural membrane for large scale deployment. Within WP3 Trelleborg produced and tested three membranes for the Symphony Wave Energy Converter. The first two membranes are produced and delivered according to Deliverable 3.6. The third is added in the final stage of the project to improve the previous version(s).

During the static tests it came out that the membranes under pressure were folding with 'ripples'. This is caused by a mismatch in the initial production diameter and the final testing diameter. But the tests also showed that the membranes are holding 1.5x their design pressure, including clamping. To check the ripples and the membrane shape under pressure, an additional membrane at the correct diameter is produced. This additional membrane is tested in the last month of WETFEET.

This deliverable is an outlook to the large scale deployment of the membrane as breakthrough component. This means the implications for scaling up in numbers (more membranes) and size (larger membranes). If the Symphony WEC is deployed at a large scale, the device will be larger and more have to be produced. The membrane has several functions in the Symphony design which should all be kept with scaling in numbers and size. These membrane functions are:

- guiding and centering the hull and main structure of Symphony;
- the membrane as bearing for the vertical movement;
- the membrane as carrier of the working fluid to run the WEC internal turbine;
- the membrane is part of the end stop of the resonating system.

Scaling up in size can be done

- in radial direction (diameter);
- in length;
- by changing the inner / outer diameter distance together with the total diameter;
- increasing the working pressure.

For the membrane prototypes, an aramid fiber reinforcement is applied in a natural rubber sheet. The life time, fatigue, stresses etc. are all calculated including energy losses due to the membrane movement. Partly these numbers need to be checked by dynamic endurance tests in the future.

Longer membranes and larger diameter membranes can in principle be made without much problems. The material properties and fabrication techniques can be the same. But a higher pressure and a larger annulus (difference in outer/inner diameter) asks for a stronger reinforcement. This means stronger aramid fibers. But stronger fibers will reduce the fatigue limit and life time of the fibers. So pure on the current material choice, especially the fibers, a strong engineering job has to be done to be able to upscale the membrane in annulus and pressure. This is a fundamental issue, but on forehand not a total show stopper.

Pure on the practical side of up scaling, there are production limits. In the current production environment, membranes larger than 3.5m diameter do not fit in the oven/autoclave. Production of 6m diameter membranes ask for an investment in production facilities or re-location of the production. Also pure practically, the handling, mounting and logistics of the larger membranes have to be taken into account with up scaling. Tooling needs to be developed to handle and mount these large membranes.

Handling and mounting the larger membranes also included the clamping method. In the 1.5m version, clamp plates have been used which are close to the limit of the steel properties. Larger membranes need a re-engineered clamping method.

Overall conclusion on large scale deployment is that there are no absolute show stoppers, but quite some effort has to be put into:

- results of dynamic testing (in relation to fatigue and endurance);
- the fatigue and life time aspects of the reinforcement in lager annulus situations;
- the production, tooling and logistics of the actual production, especially beyond 3.5m diameter;
- the connection of the membrane to the Symphony construction (clamping).

1. INTRODUCTION

For the WETFEET project under H2020, Trelleborg Ridderkerk (TR) has committed itself to design, manufacture and test an upper and lower structural membrane as one of the breakthrough component for a diameter 1500 mm Symphony WEC. This document is covers the design of the membrane prototypes and the extrapolation to a membrane for large scale deployment.
The specification used is the membrane specification by Teamwork Technology their reference: SY_MEM-2015-1 of 02-12-2015 (Annex 1)

2. DESIGN CRITERIA

The membrane is a reinforced rubber product. It acts as the flexible constraint between the internal medium and the outside medium. For the lower membrane the external medium is seawater and the external medium for the upper membrane is low pressure air (as close to vacuum as possible).
The internal medium is water with a maximum working pressure of 20 bar.
The picture in figure 2.1 shows a sketch of the Symphony prototype including the upper and lower membranes.

The blue arrows indicate the locations of the membranes, top the upper membrane, bottom the lower membrane. The maximum working pressure between the two membranes is 20 bar. As the pressure is contained by the surrounding steel structure the membrane only needs to withstand the pressure in axial direction. As such the maximum annulus between inner structure and outer structure creates the maximum radius (arch) to which the membrane is exposed when pressurized. The upper membrane goes through the largest annulus during its travels up and down.

For more detail on the working principle of the Symphony device, see Deliverable D2.2 and D2.3 of the WETFEET project.

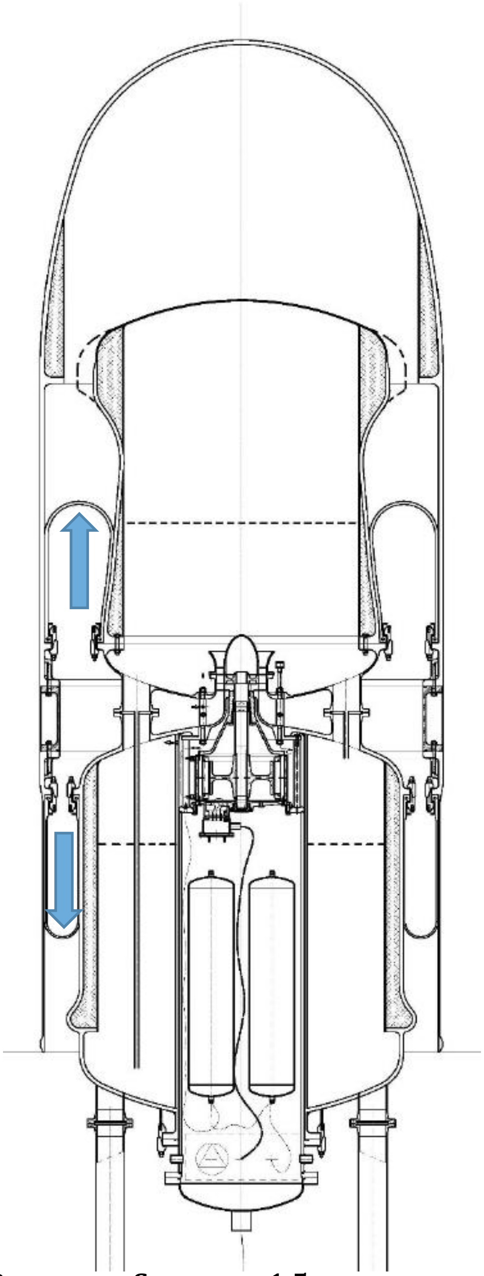


FIGURE 2.1: PROTOTYPE SYMPHONY 1.5M DIAMETER

The following pictures show the dimensions of the membrane prototypes. The membranes are produced and tested as part of the underlying project. The actual produced membranes are presented in WETFEET Deliverable D3.6.

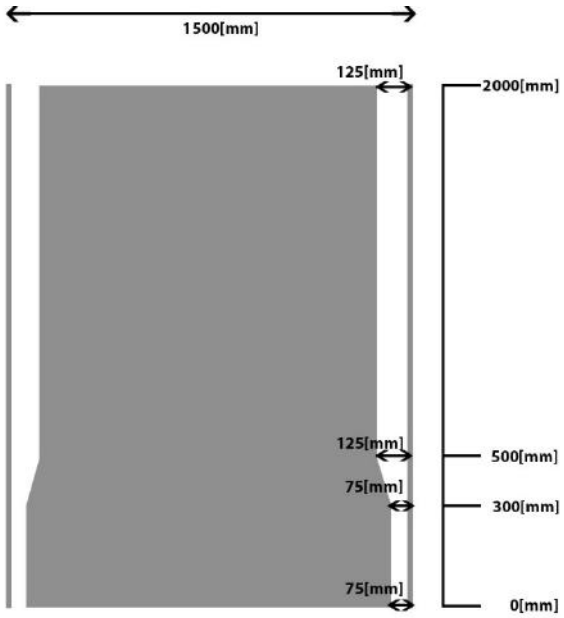


FIGURE 2.2 LOWER PART OF THE SYMPHONY STRUCTURE, THE WALL AGAINST WHICH THE MEMBRANE WILL ROLL.

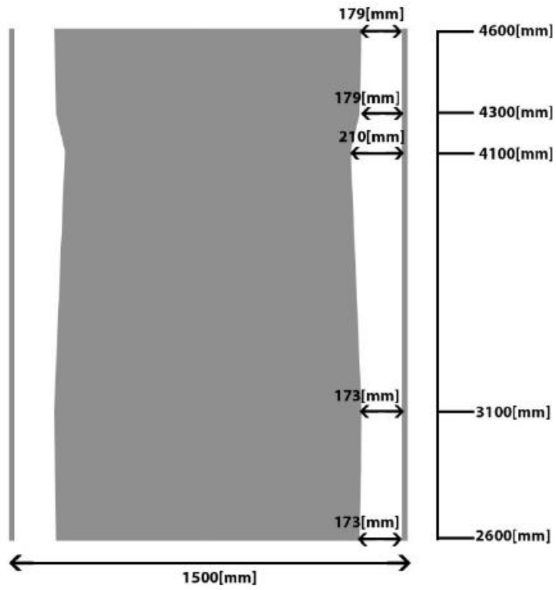


FIGURE 2.3 UPPER PART OF THE SYMPHONY STRUCTURE, THE UPPER WALL AGAINST WHICH THE MEMBRANE WILL ROLL.

The following design criteria can be derived from the above structure layout and dimensions.

Description	Value	Units
Outside diameter	1500	mm
Maximum average annulus	210	mm
Maximum working pressure	20	bar
Movement up and down	±2000	mm
Lateral movement Upper part	±75	mm
Internal fixation diameter Upper	1154	mm
Internal fixation diameter Lower	1250	Mm
Design load factor for Reinforced Rubber	4	

TABLE 2.1. 1500MM MEMBRANE SPECIFICATIONS

3. MATERIALS

The materials chosen for the membranes are Aramid cord reinforcement and Natural Rubber. Natural Rubber has the best properties in fatigue, hysteresis, durability and (sea)water resistance. Trelleborg has much experience in using natural rubber for many heavy duty applications.

3.1 Aramid reinforcement aspects and considerations

Following are some considerations on the current (1500mm) prototype and scaling up to larger diameters in respect to the reinforcement fibers.

- Reinforcement material: aramid cord
- Maximum virgin strength currently used is 1050 N/mm
- Higher strength results will introduce a lower fatigue life
- This was checked and confirmed by the Aramid producer Teijin and is a material phenomenon
- The lesser fatigue resistance of even stronger Aramid cord materials was proven during one of our internal development projects for which we had stronger cords developed. During the lifetime estimation of the product the outcome was that the fatigue resistance had come down by a factor 8.

As a consequence the strength of 1050 N/mm is the upper limit at direct up scaling for larger diameters, or at least a the same fatigue properties. Otherwise the reinforcement need to be re-engineered or the maximum load should be kept under the 1050 N/mm limit.

- Using a maximum work pressure of 20 bar, future large scale membranes have a challenge to reach a larger annulus between inner and outer part then the current gab between the inner and outer diameter.
- Using the current maximum average annulus of 210 mm, a maximum lateral movement of ±75 mm resulting in a maximum annulus of 285 mm.

Up-scaling the membrane will reach the limit of the aramid cord reinforcement fibers or limit the maximum annulus of the membrane. This is not a full show stopper, but a serious aspect for future developments to tackle. Alternative reinforcement has to be found, or different ways of applying aramid.

3.2 Natural Rubber

In respect to the choice of natural rubber as material can be concluded the following.
- The sealing material that will be used is Natural Rubber (NR)
- NR has very good mechanical properties
- And NR has a good resistance against fatigue

There are no serious issues scaling up the membranes using natural rubber.

4. DESIGN OF THE MEMBRANE PROTOTYPE

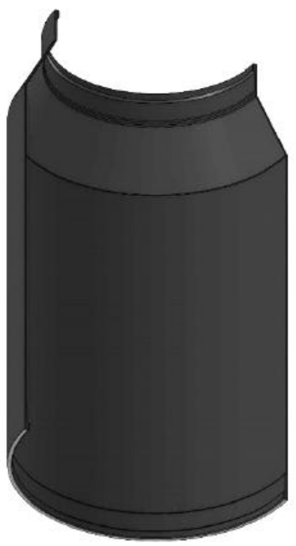
4.1 Membrane design

The basic design of the membrane is a reinforced rubber sheet built around a predefined steel drum. The reinforced sheet is built from an inner and outer layer of rubber with two layers of Aramid cord fabric in between under an angle of 10° with the axis of the membrane. After the build-up process, the membranes are vulcanization and released from the drum.

During installation in the Symphony device or in the bench test device, the inner flange will be folded inwards and fixed against the inner structure of Symphony/Bench test using clamping plates.

Lower as built

Lower with inwards folded inner flange



Upper as built

Upper with inwards folded inner flange

FIGURE 4.1 MEMBRANE SECTION VIEW

The next figure shows how the membrane will look after installation

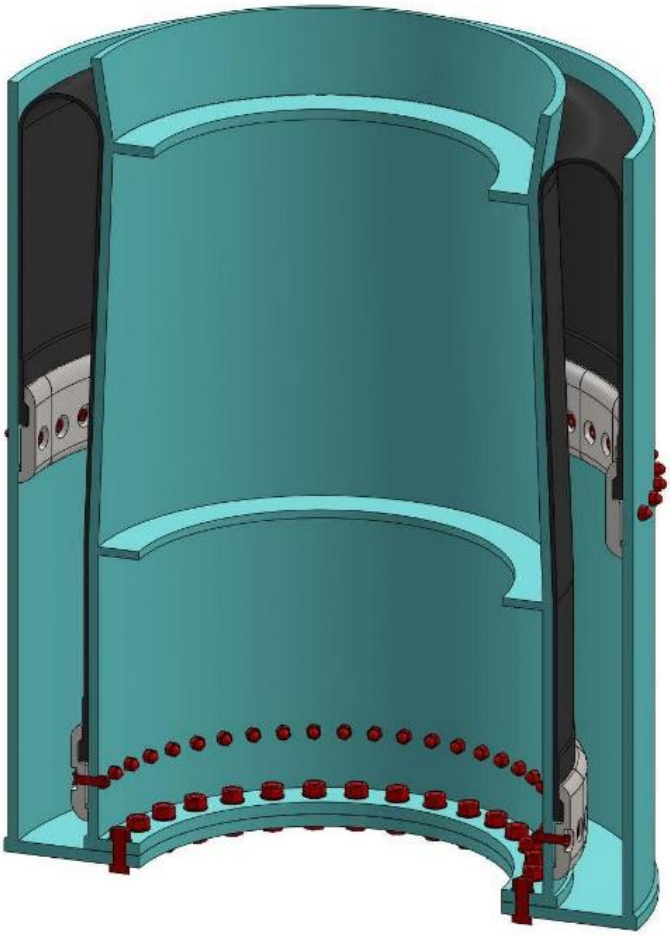


FIGURE 4.2 SECTION VIEW OF INSTALLED MEMBRANE

4.2 Membrane strength

In Appendix 2 the calculations are shown used to validate the membrane.
The remaining safety factor is 1.9 for the Upper membrane
The remaining safety factor is 2.7 for the Lower membrane

4.3 Estimate of loss of energy

During the vertical reciprocal movements of the device the membranes are constantly bending and unbending in vertical direction and reducing and increasing in diameter in horizontal direction. In this continuous process the rubber is stretched and compressed over and over again and energy is lost. When the membrane is forced straight again and returning to its original larger diameter part of the energy is given back. The loss due to this hysteresis effect of the rubber is approximately 30% based on measurements carried out on the NR compound used.

Appendix 3 shows the calculation for the estimation of the energy loss.
The upper membrane loss = 23.6 kJ.
The Lower membrane loss = 15.6 kJ

4.4 Clamping plates

The clamping plates are checked for a clamping pressure of 4.2 MPa.
This is the pressure they have to hold at the maximum pressure inside the membrane.
In total four different clamping plates are used, all four types have been checked using FEA.
The clamping plates differ for inner en outer clamping and for the upper en lower membrane.

Appendix 4 shows and example of the FEA analysis.

An extensive analysis using Solid Works is done to determine the strength and stresses of the 4 types of clamping plates. As result from these studies, the first design of the plates had to be changed. But for the re-designed and analyzed clamping plates the stresses and strains stay within the material limitations.

For large scale applications, the method of clamping should be updated and made less complicated. But from strength and specification point of view, the clamps work at 20 bar, also in the large scale and up scaled situation.

5. DESIGN OF LARGE SCALE MEMBRANE

Chapter 5 focuses on different options for up scaling towards large(r) membranes.

The prototype of the membrane used within the WETFEET project for testing has been made for a 1,5m prototype Symphony. For the large scale membrane, a 6 meter diameter Symphony device is taken as reference. The specifications of a 6m Symphony are shown in the figure below.

Trelleborg produced a rubber membrane of 1.5m which is tested statically up to 30 bar pressure, not yet installed into the Symphony Device. But it can be installed in a later stadium.

Symphony Wave Power

Specifications

Length: **32 m**

Diameter: **6 m**

Max continuous power output: **600 kW**
Nameplate power output: **1200 kW**

FIGURE 4.3 SYMPHONY 6M SPECIFICATIONS

In the Symphony, the membrane is used as a multifunctional component. It has the function of a bearing, guidance system, end buffer and carrier of the working fluid (water). The 6m Symphony device will be exposed to the following condition, these are the maximum conditions under normal operation.

$Height\ to\ water\ surface = 5\ m$
$Hydrostatic\ Force = 2292\ kN$
$Max\ wave\ height = 10m$
$Max\ amplitude = 5m$
$Wave\ Force\ max = 2015\ kN$
$Moving\ weight = 64000\ ton$

5.1 Membrane design considerations

For the large (6 meter) Symphony, a larger membrane structure is needed. Up scaling the membrane can be done in multiple ways, in order to extract the power aimed for and to be able to 'feed' the PTO with the amount of working fluid to extract the power. At the same time, the membrane should still also fulfill its other functions.

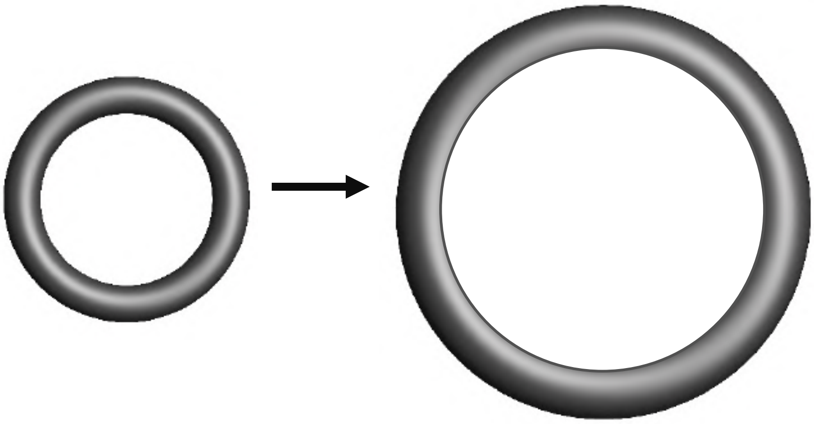


FIGURE 4.4 ILLUSTRATION OF INCREASING MEMBRANE DIAMETER SIZE

1st option for up scaling: Scaling the diameter.
Increasing the membrane diameter will result in a membrane taking care of all functions (bearing, working fluid, end buffer, etc.). The amount of working fluid is increased making it possible to work with larger flows in the PTO to extract energy. Increasing the membrane diameter gives the same loads on the aramid fibers compared to the 1500 mm prototype. And similar production methods can be used. Pure practically the currently available production tools and factory sizes restrict the diameter of the membrane at a maximum of 3500mm at the Trelleborg production facilities. Larger membranes require new or other (purpose) made production plants. This comes with large investments, but to method and principle is applicable for 6m diameter or even more.

2nd option for up scaling: Increasing membrane length
Increasing the membrane length allows the stroke of the wave energy device to be longer. This has a proportional impact on the extracted wave power. The longer stroke can create a larger volume displacement. Similar production methods can be used when up scaling the membrane. No special or different reinforcements are required because the loads in the material remain the same.

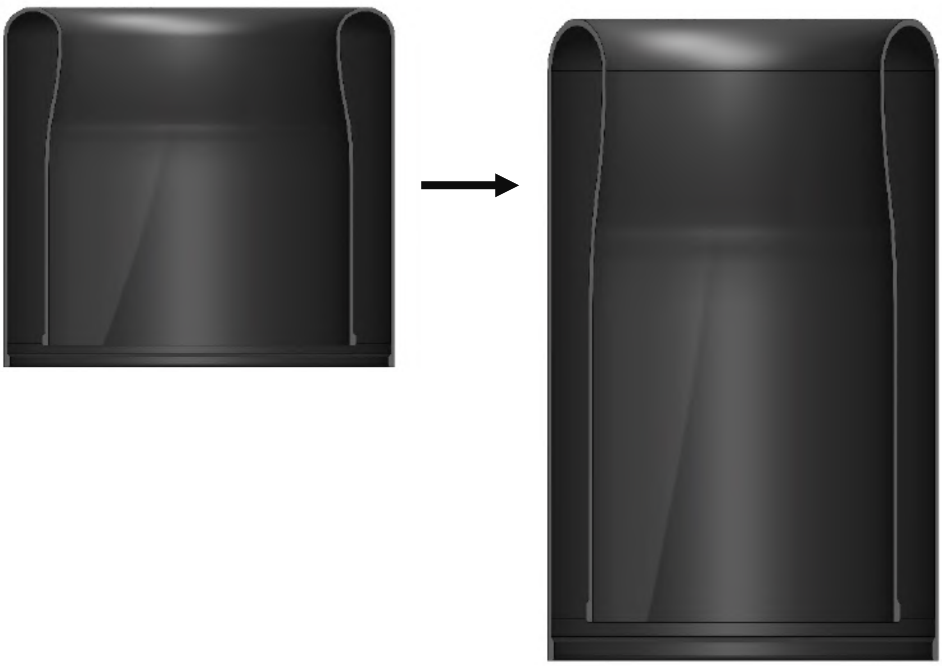


FIGURE 4.5 ILLUSTRATION OF INCREASING MEMBRANE LENGTH

3rd option for up scaling: Increasing annulus

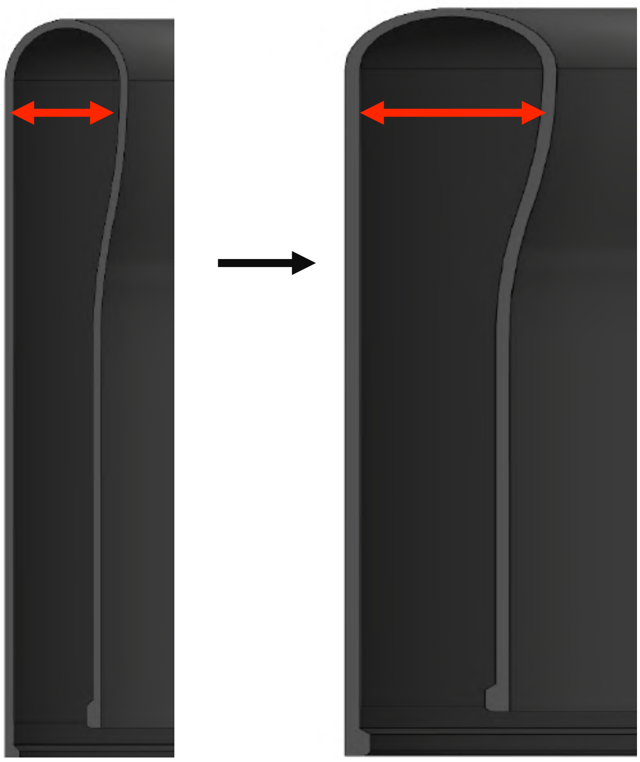


FIGURE 4.6 INCREASE OF ANNULUS AS WAY TO UP SCALE THE MEMBRANE .

To increase the power output of Symphony the amount of water flowing through the turbine/PTO needs to be increased. Increasing the annulus increases also the water displacement through the PTO. But the force on the aramid fibers increases as the annulus increases. Therefore the membrane reinforced needs to be increased as well. The following adjustments can be applied in order to reinforce the membrane.

Using stronger aramid cords
Currently the membrane is reinforced using aramid fiber cords. The cords can be made stronger by increasing the amount of winding in the cords. Increasing the windings in the cords makes the material stronger but also more stiff. The downside of using this strategy is that the fatigue lifetime of the aramid fiber decreases.

Using multiple layers of reinforcement
The lay-up of the aramid fibers inside the membrane can be multiplied. In Theory this could share the loads on the aramid fibers. Aramid fibers are extremely stiff and barely stretch before breaking. There is a risk that the force is only applied to the shortest fiber inside the composition. The second risk that occurs using this method is possible delamination between layers.

So increasing the annulus at least gives some challenges on the reinforcement, but can be done. Big benefit is the increased space for clamping or attaching the membrane to the Symphony.

4th option for up scaling: Increasing Maximum pressure

Increasing the maximum pressure allows the Symphony PTO to operate at a higher pressure differential, this could increase the turbine efficiency and lower the overall RPM of the turbine.

For increasing the maximum pressure inside the membrane the same adjustments are required as increasing the annulus: improved reinforcement. The same conclusion yields, the fibers can be made stronger, but it will have a down side effect on the fatigue lifetime.

5.2 Design large scale membrane (6m diameter)

All together, taking the scaling options in consideration a first design of a up scaled membrane set is made. To keep not only the function of transporting the working fluid, but also the bearing, centering and end stop function of the membrane, the diameter of the membrane needs to go with the diameter of Symphony. Or a total new interior design of Symphony would be needed. It good be made out of 1.5m section within a overall hull of 6m. For consideration on the other membrane functions, read also the remaining paragraphs of this chapter.

So the annulus is enlarged, the length is increased and the diameter is stretched to 6m.
This gives the conclude challenge to come with good reinforcement without losing on fatigue lifetime. This is a serious develop study not yet performed.

On top of that, the current production facilities can not produced 6m diameter membranes.

Overall conclusion in relation to the large scale deployment of structural membranes is that up to 3.5m diameter the current design and method can be used. From 3.5m tot 6m(+), investments, modifications and adjustments in the design and infrastructure need to be made. But no 100% show stoppers have come up so far.

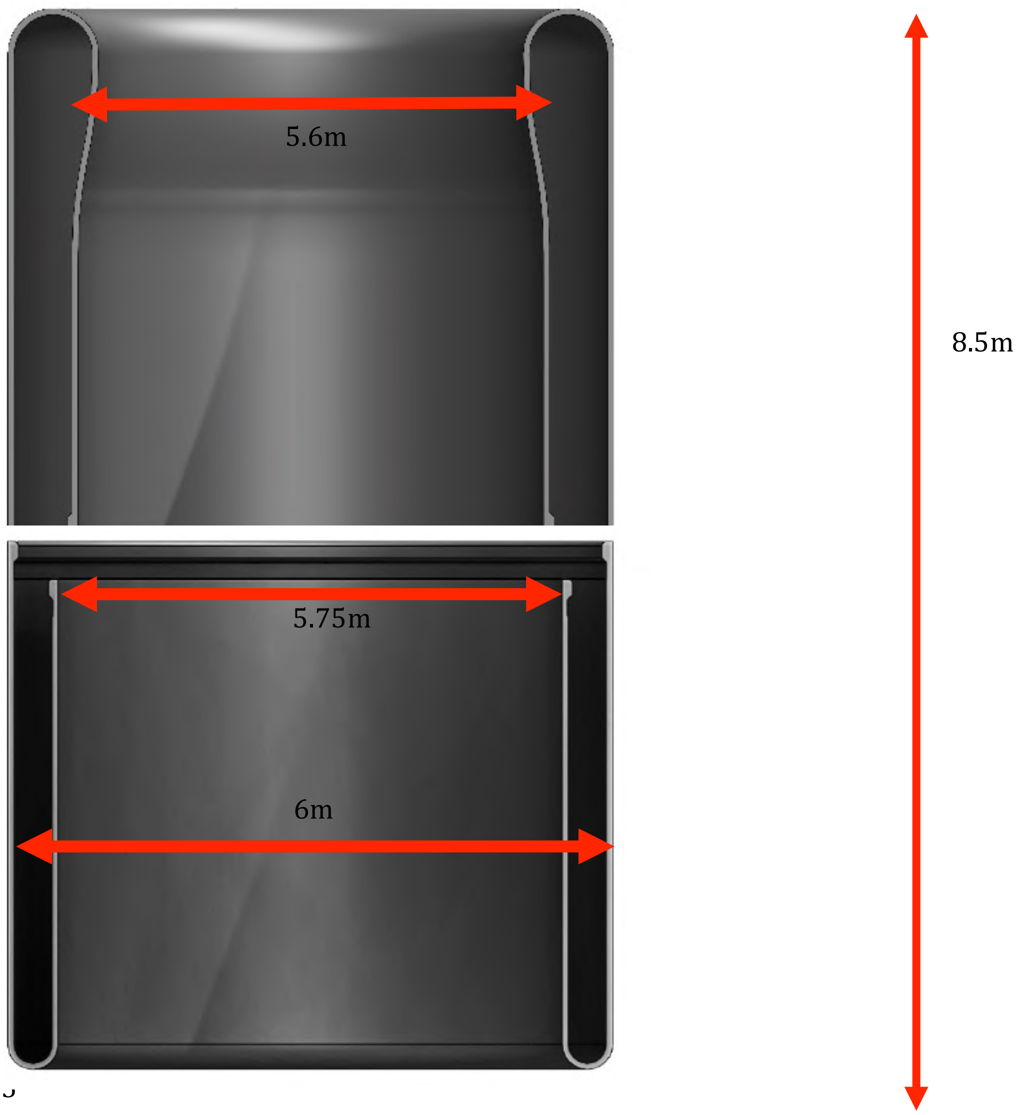


FIGURE 5.1 LARGE SCALE MEMBRANE SPECIFICATIONS OPTION 1

Neutral pressure:	15	[bar]
Maximum resulting pressure @ Hs 10 :	25	[bar]
Minimum resulting pressure @Hs 10 :	5	[bar]
Total membrane length:		
Outer diameter:	6.0	[m]
Thickness	+/- 10	[mm]

Reinforcement specs

Fibre material	Aramid fibre
Fibre angle	10 [deg]

5.3 Design large scale membrane 2

Here the option for a 3.5 m diameter membrane is worked out.

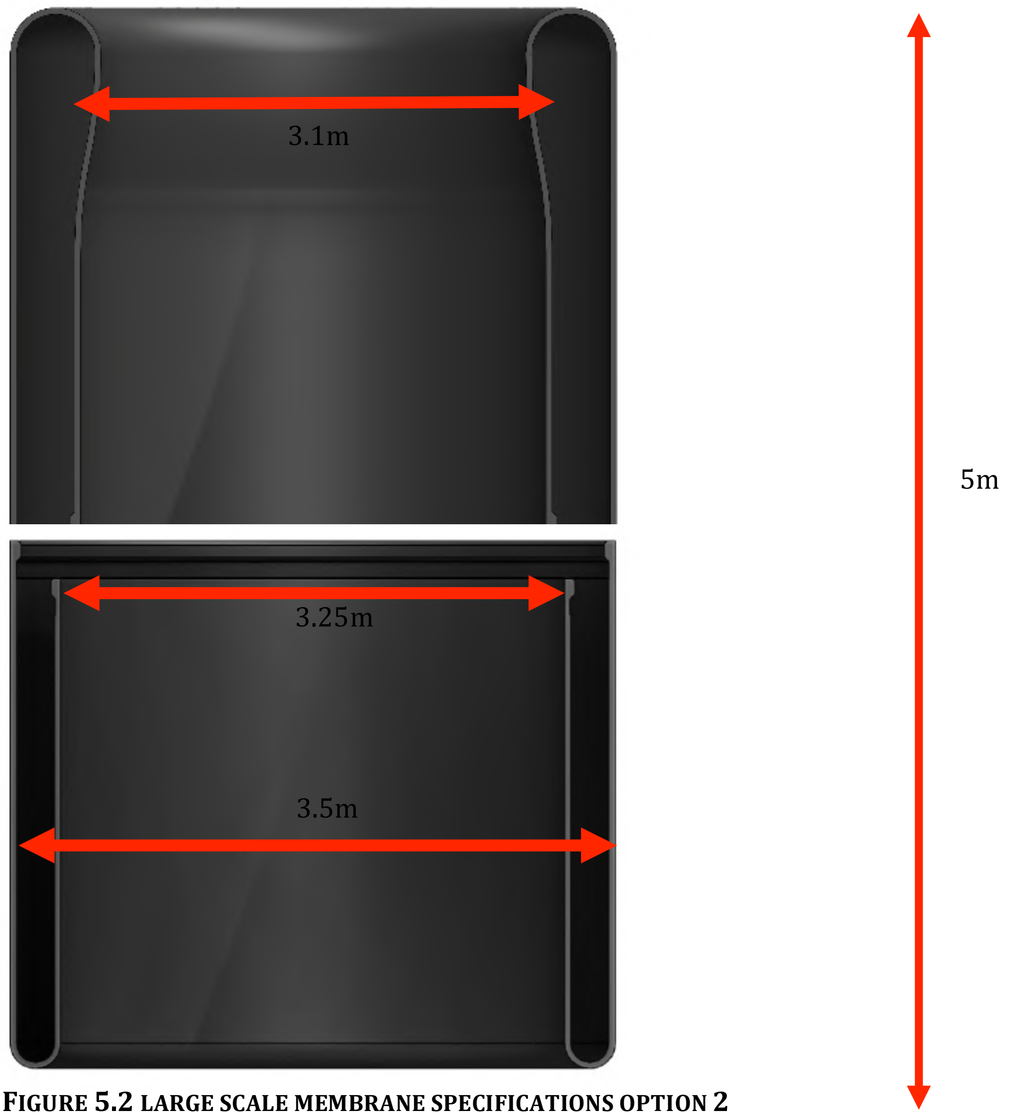


FIGURE 5.2 LARGE SCALE MEMBRANE SPECIFICATIONS OPTION 2

General specs

Rubber material:	NR	
Neutral pressure:	15	[bar]
Maximum resulting pressure @ Hs 10 :	25	[bar]
Minimum resulting pressure @Hs 10 :	5	[bar]
Total membrane length:		
Outer diameter:	3.5	[m]
Thickness	+/- 10	[mm]

Reinforcement specs

Fibre material	Aramid fibre
Fibre angle	10 [deg]

5.4 Calculations and validations of the large scale membrane

Energy losses large scale membranes
For the full scale membrane we now assume that this will be the maximum that can be made using the same method as used for the Prototype D1500.
As the annulus dimensions are the same as for the Prototype D1500 the only variable changing is the outside diameter. So the stresses and strains due to the pressure are the same as for the prototype and can be found in Appendix 2.

For the energy loss calculation we have increased the diameter from 1500 mm to 3500 mm. Using the same method as done for 1.5m diameter (see Appendix 3) the calculations for the estimation of the energy loss for 3.5m are:
For the Upper membrane: E_{loss} = 22.7 kJ
For the Lower membrane: E_{loss} = 17.8 kJ
See Appendix 6
Due to the increase in diameter, the strains due to diameter reduction get less and this explains a very small total rise in loss compared to the increase in overall diameter.

For further insight in the energy loss we have increased the diameter to 6000 mm.
Appendix 7 shows the calculation for the estimation of the energy loss.
For the Upper membrane: E_{loss} = 24.6 kJ
For the Lower membrane: E_{loss} = 21.7 kJ

5.5 Full scale Membrane

Based on the above calculations and our experience with large and very large rubber products Trelleborg can make membranes for diameter 3500 mm Symphony device.

Investing in other larger equipment will make it possible to go to dimensions of 2-3 times as large as long as we keep the dimensions of the annulus the same as for the prototype D1500.

In Appendix 8 the challenges and solutions are given for large scale production of the membranes up to a size of Ø6000 mm. Appendix 8 is also included in Chapter 6.

6. OTHER MEMBRANE ASPECTS (intermezzo)

Chapter 6 gives some background on other aspects related to the membrane, these type of considerations and calculations should be re-done in order to be sure about the large scale deployment. Chapter 7 returns to the main considerations and conclusions.

6.1 Bearing and guidance system validation

The membrane is used as bearing and guidance system. The membrane is the component that separates the housing of the wave energy converter from its internal components. The membranes centering function must be good enough in order to prevent possible impact between the housing and its internal components.

In order to see if the membranes centering force will be sufficient, calculations are made. The goal of these calculations is to define the systems stiffness and find out if the membrane's centering force is sufficient and whether the membrane's natural frequency will not become resonant with the frequency of the ocean wave's.
On the image below we see the top view cut out of the Symphony where the dark grey line is the outer cylinder and the yellow surface represents the internal components of the Symphony. The outer cylinder is being pushed, in horizontal direction caused by the horizontal forces of the ocean wave. The wave force is acting perpendicular to the heave direction of the Symphony. The Force of the wave is defined as Fwave. The centering force caused by the membrane is defined as Fcm.

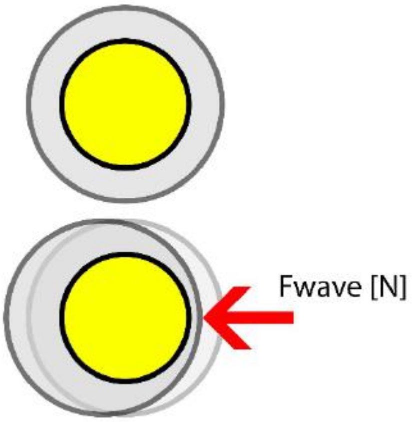
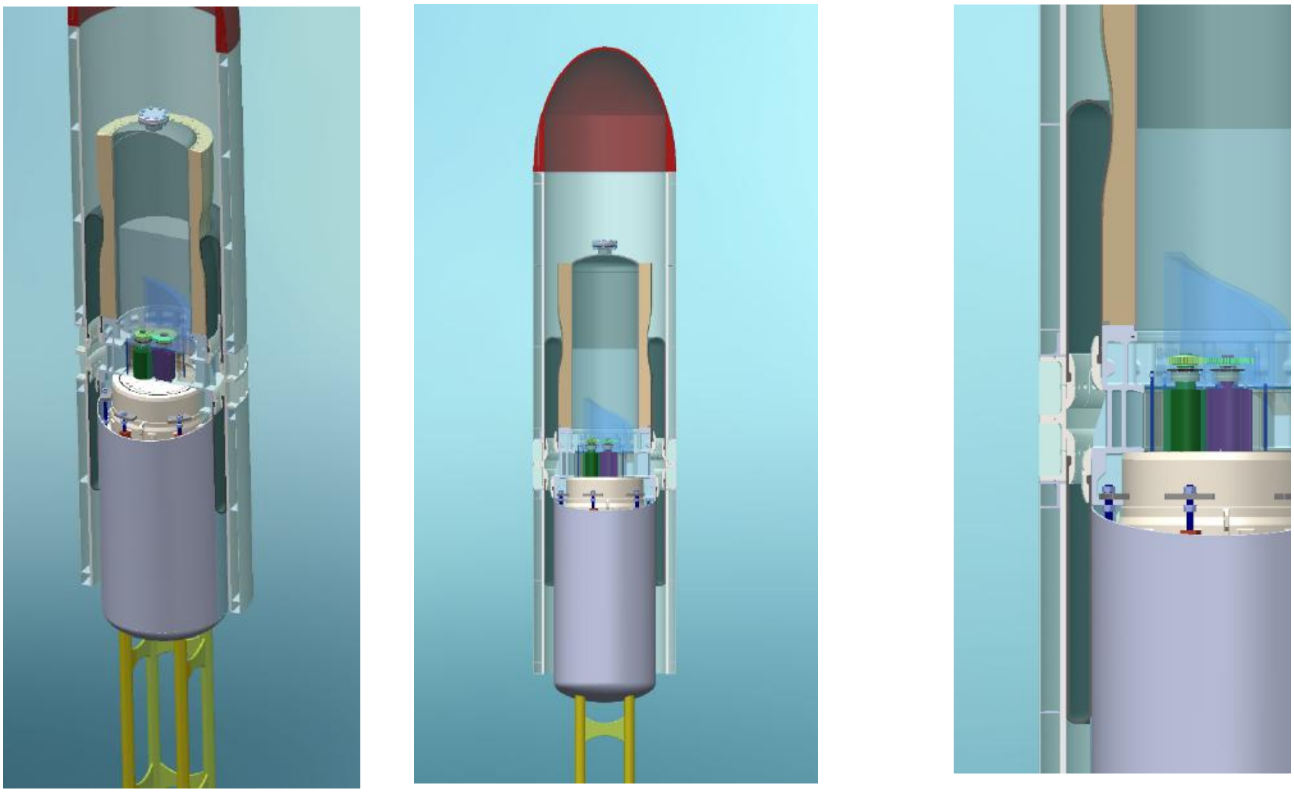


FIGURE 6.1 TOP VIEW HORIZONTAL MOVEMENT OF THE MEMBRANE

The outer cylinder will me be moving sideways till the equilibrium has reached. There are two factors that cause the membrane to center itself when it is being moved horizontal: water pressure acting on the surface and the membrane's material stiffness and strain. The membrane has a upper part and a lower part. Both parts center the outer cylinder. In order to predict the center effect of the membrane, calculations are made.



Section view Side view Zoom

FIGURE 6.2 SECTION VIEW OF THE MEMBRANE

6.2 Water pressure center force

In order to calculate the center effect caused by the water pressure the assumption is made that the membrane's material stiffness and strain are negligible. The centering force caused by water is determined by the difference in working surface area between the left and the right side of the membrane multiplied by the water pressure. The centering force of the system is described in N/m where the distance is the horizontal displacement.

Membrane shape

The centering force of the water is determined by the difference in working surface area between the left and the right side of the membrane multiplied by the water pressure. In order to find out the working surface area, the membrane shape must be determined.
If the assumption is made that the membrane is completely flexible and has no strain or mass it can be considered as a massless rope. If a massless rope is virtually cut, the tension in the rope is the same at every point.

Conclusion of the membrane shape
If the assumption is made that the membrane's material stiffness and strain are negligible. The shape of the membrane not touching the surface will get a circular shape. In order to estimate the centering force of the water, a circle will be used to determine the difference in between surfaces.

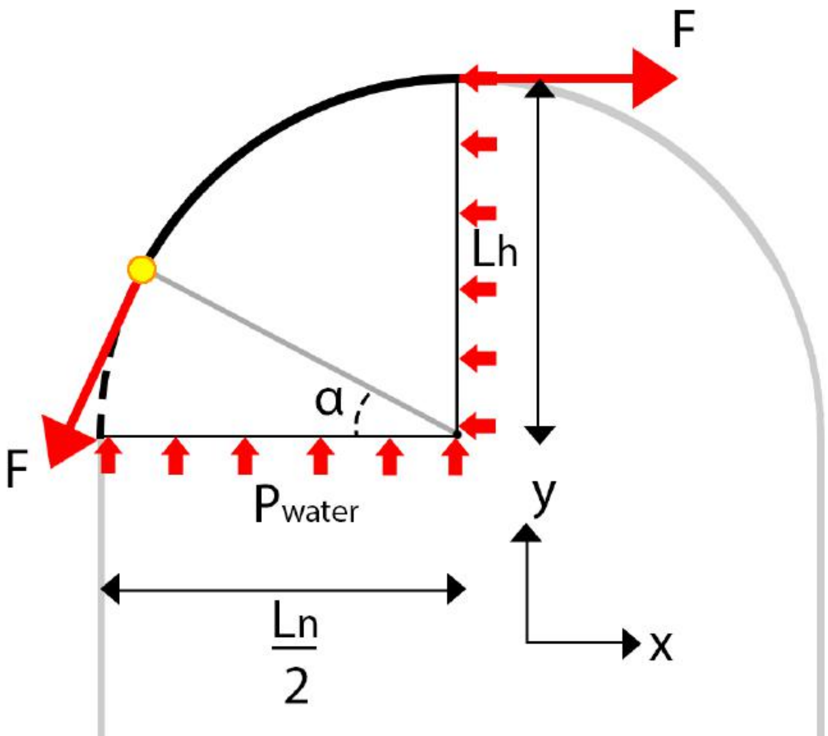


FIGURE 6.3 MEMBRANE SHAPE

Height difference vertically
The shape of the membrane not contacting the outer cylinder will become circular. The difference in height vertically is the difference of contact between the left and the right side.

$$\begin{aligned}&\frac{L_{Membrane}}{2}*\frac{1}{4}*\left(L_{Neutral\,upper\,membrane}-\Delta L_{Horizontal}\right)*\pi\\&-\frac{L_{Membrane}}{2}*\frac{1}{4}*\left(L_{Neutral\,upper\,membrane}+\Delta L_{Horizontal}\right)*\pi\\&+\frac{L_{Membrane}}{2}*\frac{1}{4}*\left(L_{Neutral\,lower\,membrane}-\Delta L_{Horizontal}\right)*\pi\\&-\frac{L_{Membrane}}{2}*\frac{1}{4}*\left(L_{Neutral\,lower\,membrane}+\Delta L_{Horizontal}\right)*\pi\end{aligned}$$

Rewriting the formula gives:

$$Height\ difference\ vertically(0\leq\Delta L_{Horizontal}<\ L_{Neutral\,lower\,membrane})\ =\Delta L_{Horizontal}*\pi$$

Significant surface

The significant surface is dimensionless constant dependent on the significant height and the significant force. The significant force is the amount of force that is working opposite to the horizontal force causing the membrane to move.

Significant height(relative) — Significant force(direction of the force)

$$\left(\left(\frac{\pi-x}{\pi}\right)*\left(\cos(x)\right)\right)$$

The significant height is the height difference between the highest touching point of the membrane and the lowest touching point at a certain point of the outer cylinder. The assumption is made that the distribution is linear. The significant force is the dependent on the direction of the force as shown bellow.

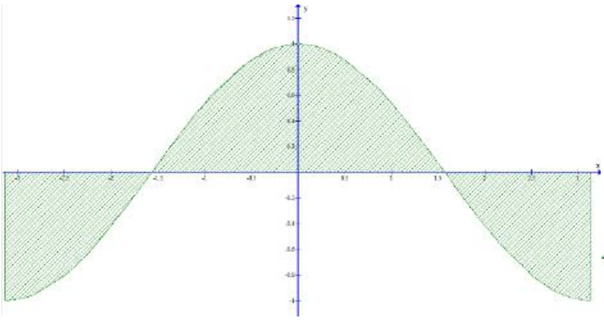


FIGURE 6.4 RELATIVE DIRECTION OF THE FORCES

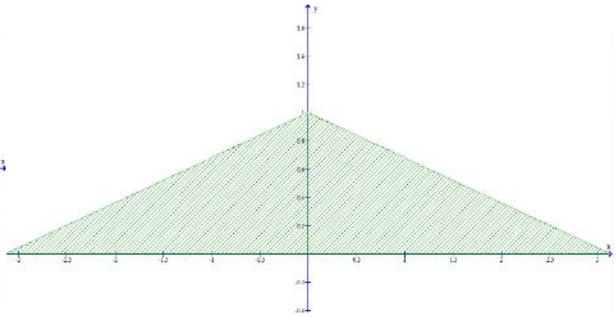


FIGURE 6.5 RELATIVE TOUCHING SURFACE

If these two formula's are multiplied and integrated, the significant surface is defined.

The function of the significant height is shown in the figure bellow.

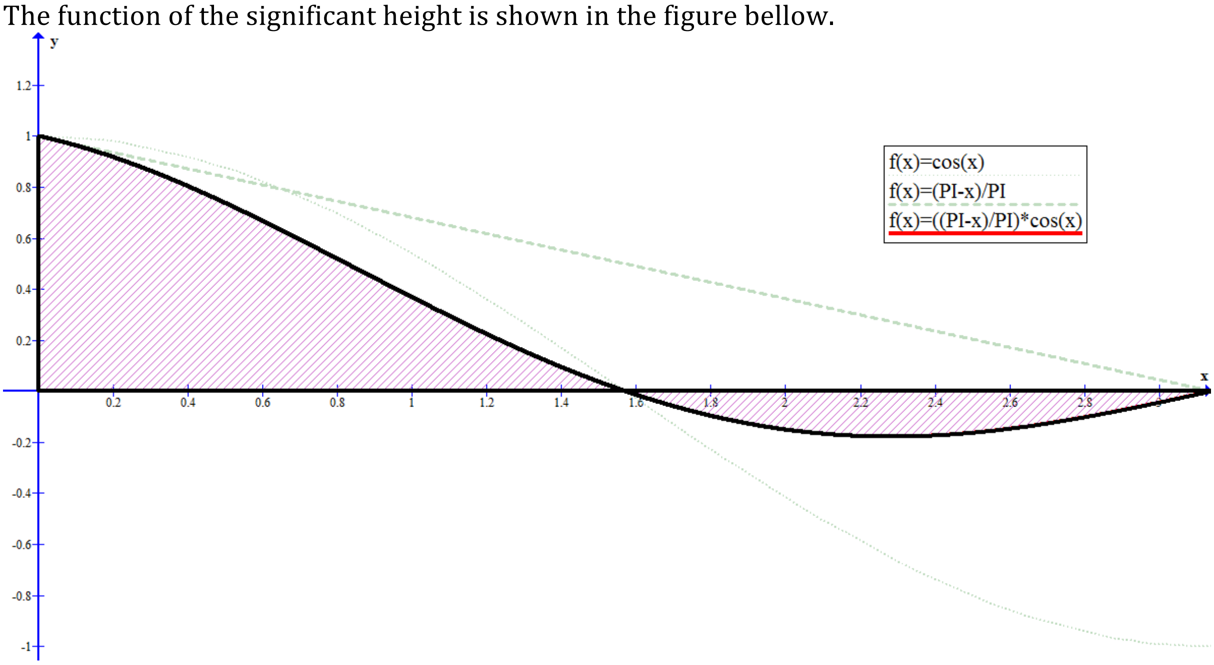


FIGURE 6.6 GRAPH SIGNIFICANT SURFACE

The shaded part is the product of the integral for 0 to π which represents the significant surface. This graph represents the significant surface for one half of the membrane touching the outer cylinder. If the graph is mirrored and added it represents the complete significant surface for the outer cylinder as shown in the figure bellow.

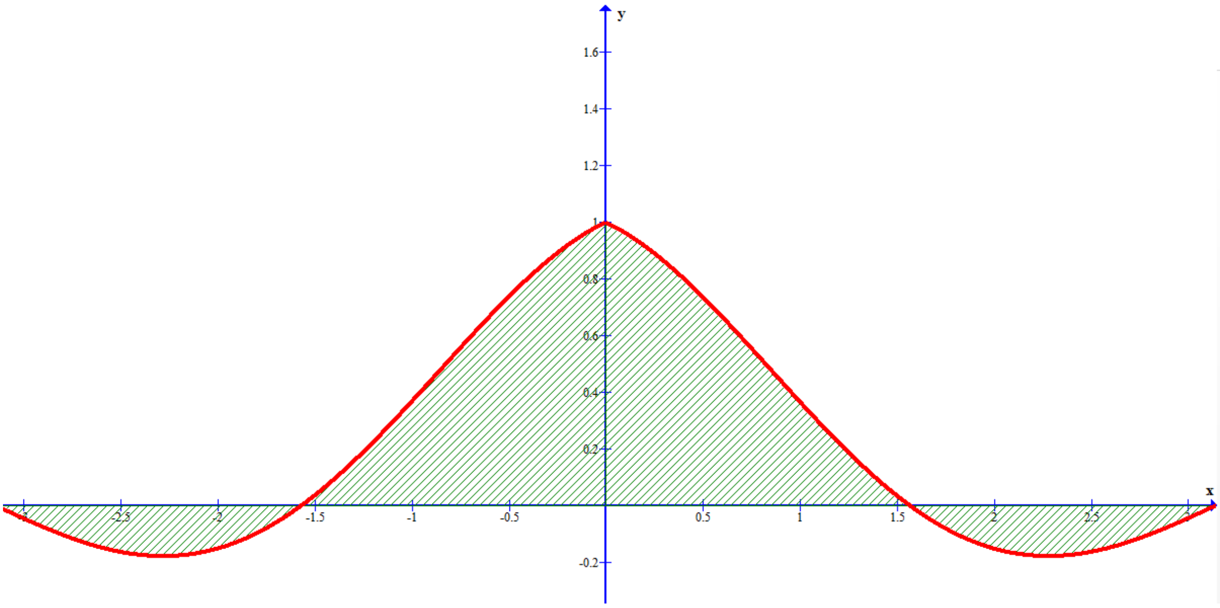


FIGURE 6.7 GRAPH SIGNIFICANT SURFACE COMPLETE

The x-axis of the graph shows the position of where radial position of where the membrane is touching the surface of the outer and inner cylinder. The y-axis shows the Significant surface. If the value of y becomes below 0 It means that the centering force membrane works in a negative way for that certain radial position.

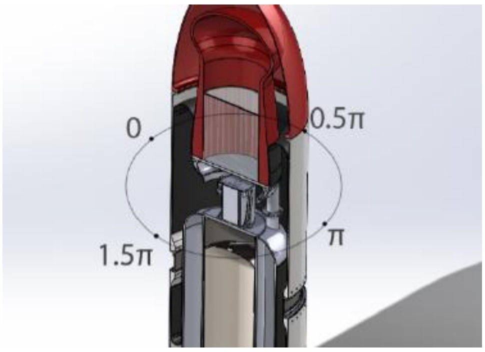


FIGURE 6.8 RESULTANT CENTER FORCE

Calculation of the membrane's stiffness

Relative significant surface coefficient

The relative significant surface coefficient is given by:

$$\frac{\left(\frac{2}{\pi}\right)}{\pi} = 0.202642367$$

This coefficient represents the ratio of the diameter multiplied by the maximum surface height difference of the membrane and the actual surface that works in the opposite direction of the wave.

Centre force [N]

$$= n * \Delta h_{membrane\ Max} * \emptyset_{inner\ cilinder} * \pi * relative\ significant\ surface\ coefficient * P_{membrane}$$

$$Spring\ constant\ (k) = 2 * 4 * 1.3\pi \frac{\left(\frac{2}{\pi}\right)}{\pi} * 1000000 \left[\frac{N}{m}\right]$$

$$Spring\ sconstant (k)\ at\ 10\ [bar] = \mathbf{1.04 * 10^7} \left[\frac{\mathbf{N}}{\mathbf{m}}\right]$$

The membrane's spring constant represents the amount of resistance that the membrane gives when a certain displacement is applied. In order to find out how much the outer cylinder could move, a simplified time domain model is introduced.

6.3 Membrane dynamics

In order to make an estimation on how the system will react in the ocean, the system of the membrane is integrated the system dynamics program Matlab. The main goal of the simulation is to see how the system will act when in operation. The membrane system is introduced in the program as a linear mass spring system.

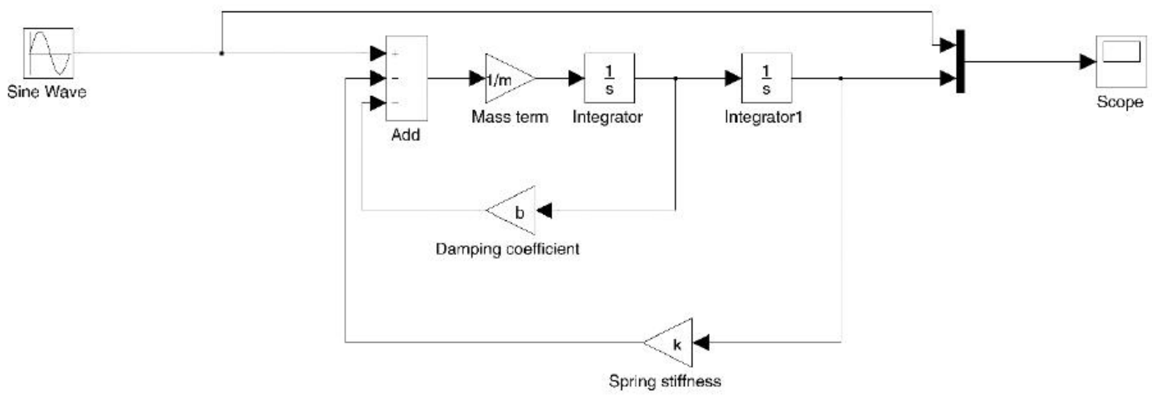


FIGURE 6.9 SIMULINK MODEL

The system has three variables that need to be determined in order to simulate the membrane. The input must also be defined.

The mass is defined by the mass of the outer cylinder including the added mass caused by movement.

Total Mass:64000 kg

The damping coefficients are defined by the drag caused by movement of the outer cylinder and the internal displacement of water. Just like the Symphony itself, the roll membrane could be considered as a mass spring system.

Situation 1: Forced displacement
The following situation is considered. The Symphony is placed in the ocean with its core completely fixed. In this situation the Symphony is exposed the most to the horizontal forces of the wave, since the core wont absorb the horizontal forces.

Goal of the simulation
The goal of this analysis is to find the membrane's natural frequency. If the natural frequency is similar to the wave frequency the system could become resonant, risking the system to break. The wave's average wave period time of Sines is about (Te)=10[s]. The wave period time spectrum taken to consideration lays between 4[s]-30[s]or 0.25[Hz]-0.04[Hz]. The scatter diagram of the site shows that smaller period time's equals smaller waves and higher period time equals higher waves. The membrane is considered to be safe from resonance if the natural frequency of the membrane is 1Hz and up or 0.01Hz and below.

Simulation setup
The outer cylinder is moved horizontally by 0,01 meters sideways, with the core still fixed at the same spot. The outer cylinder is released. The goal of this simulation test is to find out what the frequency of the membrane is. There is a potential danger of the membrane's frequency being in phase with the main wave. If the membrane frequency is in faze with the wave's frequency, the system becomes resonant, which could damage the Symphony's components. The horizontal position of the outer cylinder is shown in the graph below.

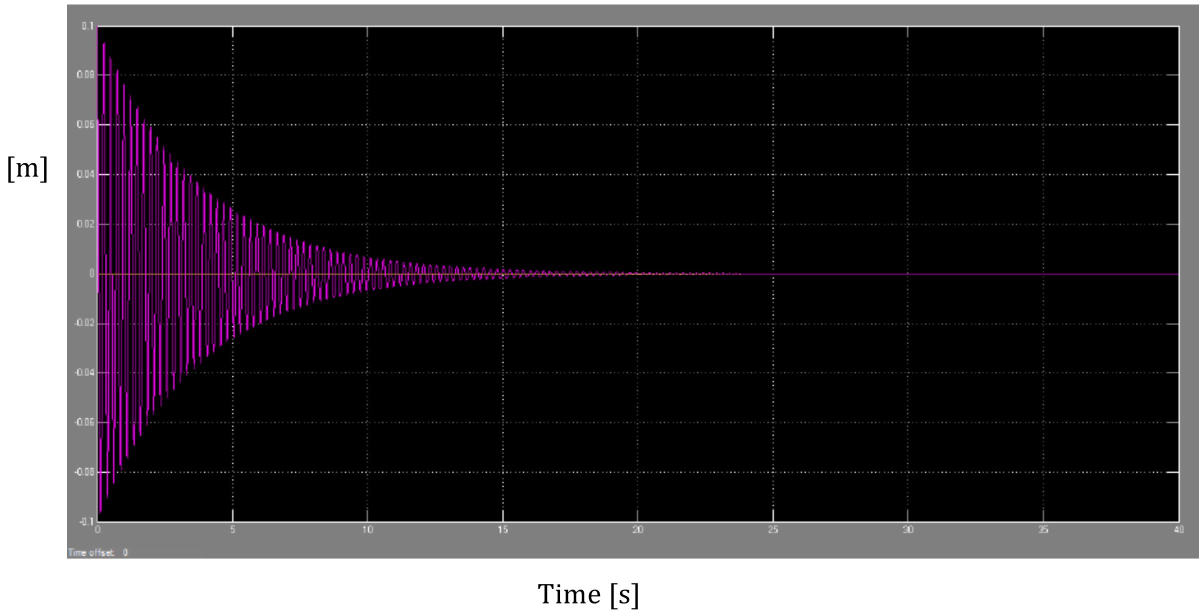


FIGURE 6.10 NATURAL FREQUENCY OF THE MEMBRANE

In order to move the cylinder 0,01 meter 104 [kN] is needed. The system oscillates and damps. The cylinder damps out at a very high frequency. It is important that the frequency of the membrane is different from the wave. If it would be in synch with the frequency of the wave, it could become unstable. According to this graph the membranes own frequency is about 2 hertz. The main wave's frequency band is far below one hertz.

Situation 2: adding a wave.

Goal of the simulation
The goal of this analysis is to see how much the membrane would move in a certain sea state. If simulation shows that the horizontal movement is more than the span between the inner and the outer cylinder, the system is at risk of being damaged. Sideways movement could also make the system less efficient.

Simulation Setup
The membrane is introduced as a mass spring system as shown before. The spring stiffness of the membrane remains the same. The input of the system is representing the excitation force of the wave acting sideways on the system. The excitation force acting on the Symphony depends on the geometry of the submerged object, its position in the water and the size and period time of the wave. The excitation force is calculated by an a fluid dynamics program(WAMIT). The values of these excitation forces are shown in the graph bellow.

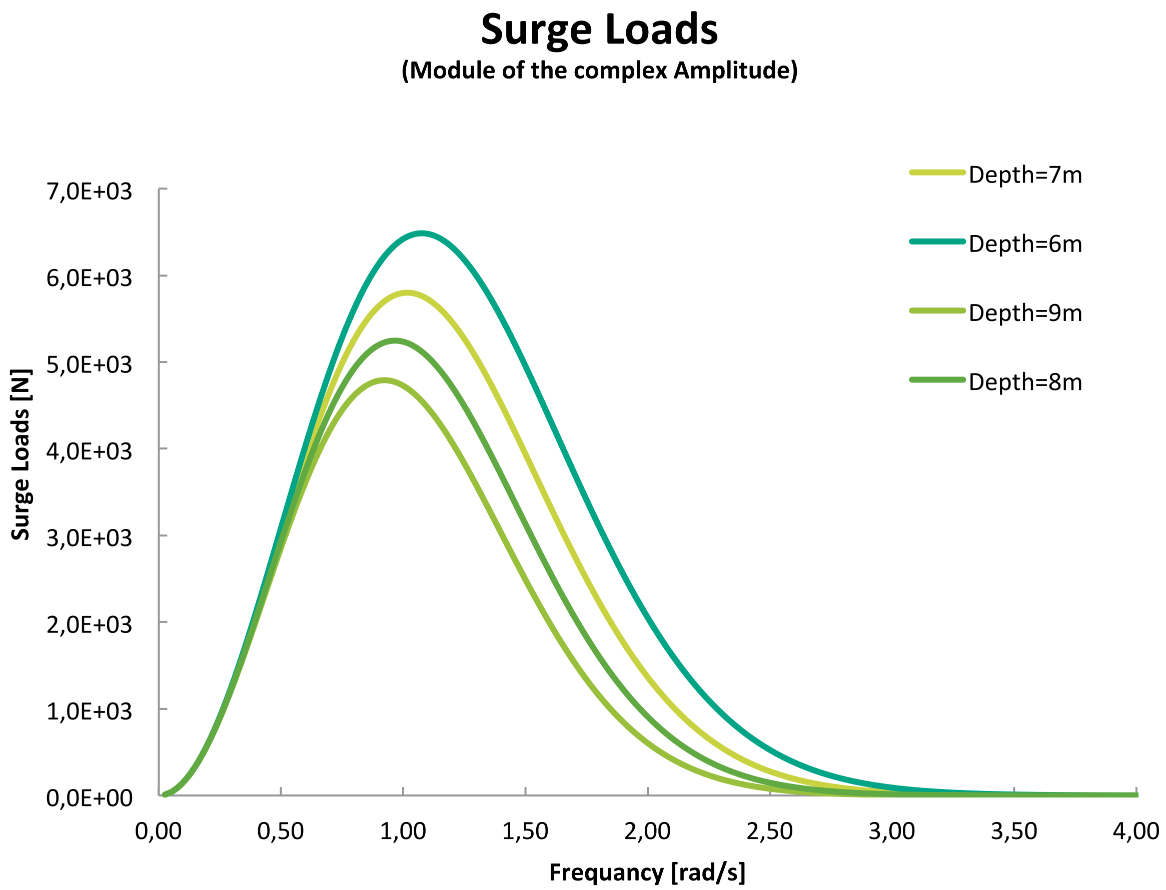
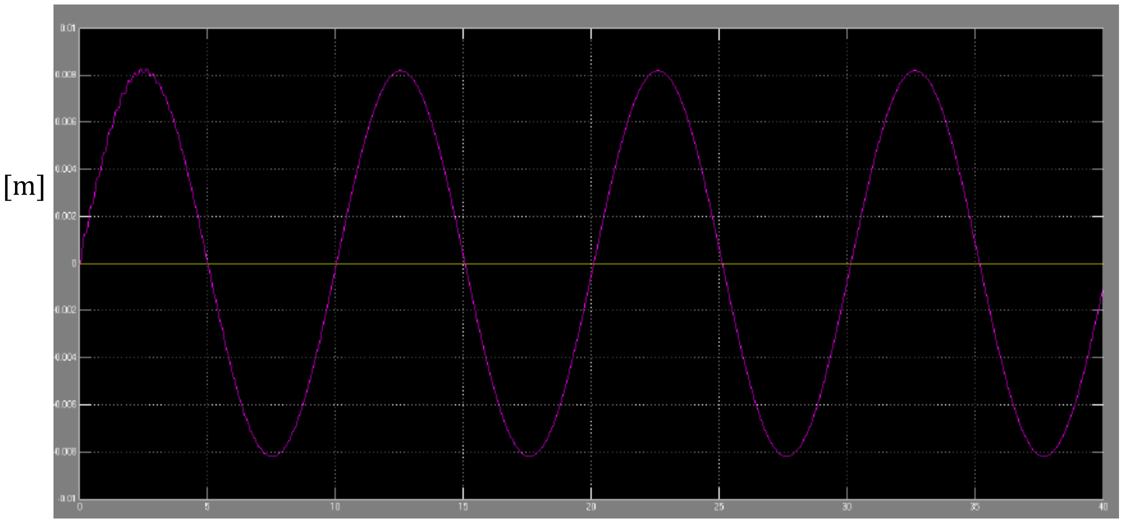


FIGURE 6.11 HORIZONTAL FORCE PER AMPLITUDE

For this simulation the Symphony is fixed to the bottom of the ocean. The inner cylinder is fixed and cannot move in any direction. For this case the horizontal displacement the biggest because the excitation force is completely absorbed by the membrane. This is a worst case scenario since the inner parts of the Symphony are able to move horizontally.



Maximum discplacement during operation: 10 mm
Seastate: Hs=5[m] Period time band : 10-20s

Maximum discplacement during severe weather conditions: 12.5mm
Seastate: Hs=10m Period time band : 12.5-25 s

Conclusion of the membrane's centering function
The simulations and calculation show that the system will not move more than 10mm when operational and not more than 12.5 mm in severe conditions when the inner parts of the Symphony are completely fixed. These displacements will not damage the internal components due to impact. The simulation shows that the natural frequency of the membrane is not in phase with the wave's frequency band, so the membrane will not be resonant with the waves.

Assumptions and their influence
In the simulation the assumptions where made that the inner cylinder is fixed, Significant height distribution is linear and the membrane's material properties are negligible. The assumptions made during the simulation have a negative effect on the end results, so the simulation represents a worst case scenario. The end results might not show a representative displacement and natural frequency in the reality. In reality, the centering force will most likely be even better.

7. Large scale deployment of membranes

Certain challenges/unknown subjects need to be tackled before large scale deployment of the membranes can take place. These are the following.

-Limited Annulus/pressure increment.
Scaling up the membranes creates more force acting on the Symphony. This needs to be compensated for by increasing the pressure or annulus in the membrane. Increasing the annulus or pressure required reinforcement of the membranes, which decreases the fatigue lifetime significantly.

-Fatigue lifetime
Fatigue lifetime of the large scale membranes is yet unknown. Dynamic tests of the membrane need to be done in the future before large scale deployment.

-Hand ability
The large membranes are heavy and require special equipment for installation and de-installation. Special tools need to be made for the installation and de-installation of large membranes

-P**roduction methods and facilities**
Currently existing production facilities allow a maximum diameter of the role membrane of 3.5m. custom facilities need to be setup in order to produce larger membranes. More information regarding production of the large scale membrane is shown on the next page.

7.1 Production challenges related to large scale production

Below table shows the challenges to be solved in case of large scale production and possible solutions

Size mm	Symphony 1 pc / week	Measures/ solutions	Symphony 2 pcs / week	Measures/ solutions
Ø1500	Capacity of building tool compared to building hours required	Additional Tool required	Capacity of building tools compared to building hours required	Additional Tools required
Ø3500	Challenging are the design and the dimensions of the building Tool	Technically feasible requires design and production time	Capacity of building tools compared to building hours required	Increase number of Tools
Ø6000	1] Challenging are the design and the dimensions of the building Tool	Technically feasible requires design and production time	1] Challenging are the design and the dimensions of the building Tool	Increase number of Tools
	2] Also challenging is the vulcanisation system to be applied to the tool	Technically feasible requires design and production time	2] Also challenging is the vulcanisation system to be applied to the tools	Technically feasible requires design and production time
	3] Find a proper location	To be addressed when there is an actual requirement	3] Find a proper location	To be addressed when there is an actual requirement
	4] Time frame needed to accomplish 1] to 3]	To be addressed when there is an actual requirement	4] Time frame needed to accomplish 1] to 3]	To be addressed when there is an actual requirement

The preliminary schedule (estimate) for the start up for the production of Ø6000 membranes shows a total time of roughly one year.

Start-up time for the production of Ø3500 membranes is estimated to be approximately 6 months.

Attachments

Following Appendices are part of this document

Appendix 1	Membrane specs
Appendix 2	Membrane Strenght
Appendix 3	Energy loss calculations
Appendix 4	Example FEA clamping plate prototype.
Appendix 5	FEA membrane
Appendix 6	Loss of membrane 3500mm
Appendix 7	Loss of membrane 6000mm
Appendix 8	Challenges for full scale deployment

Appendix I: Membrane specifications of the 1.5m prototype

Technical Note: SY_MEM-2015-1

Membrane specifications of the 1.5[m] prototype

Hans van Noorloos

Subject	Specifications of the membrane of the 1.5[m] prototype
Abstract	This report is a specification report of the membrane of the Symphony Wave Power 1,5[m] prototype. The specifications in this report have been composed before the engineering phase of the membrane has started. The specifications described are based on the functionality and dimensions of the membrane. Material specifications and detailed specifications of the connections are not included. The document can be used as a starting point of the engineering of the membrane.

Revisions			
Revision	Name	Date	Approved
v0	Hans van Noorloos	20-11-2015	
V0.1	Roelof Schuitema	2-12-2015	
V1.0	Hans van Noorloos	02-12-2015	
			Waiting for Authorization

Introduction

This report is a specification report of the membrane of the Symphony Wave Power 1,5[m] prototype. The specifications in this report have been composed before the engineering phase of the membrane has started. The specifications described are based on the functionality and dimensions of the membrane. Material specifications and detailed specifications of the connections are not included. The document can be used as a starting point of the engineering of the membrane.

Symphony Principle

The membrane is part of the Symphony wave energy converter. The Symphony wave energy converters transforms energy from ocean waves into electrical energy. At first a prototype scale model will be made of the Symphony. An illustration of the Symphony is shown in the figure bellow:

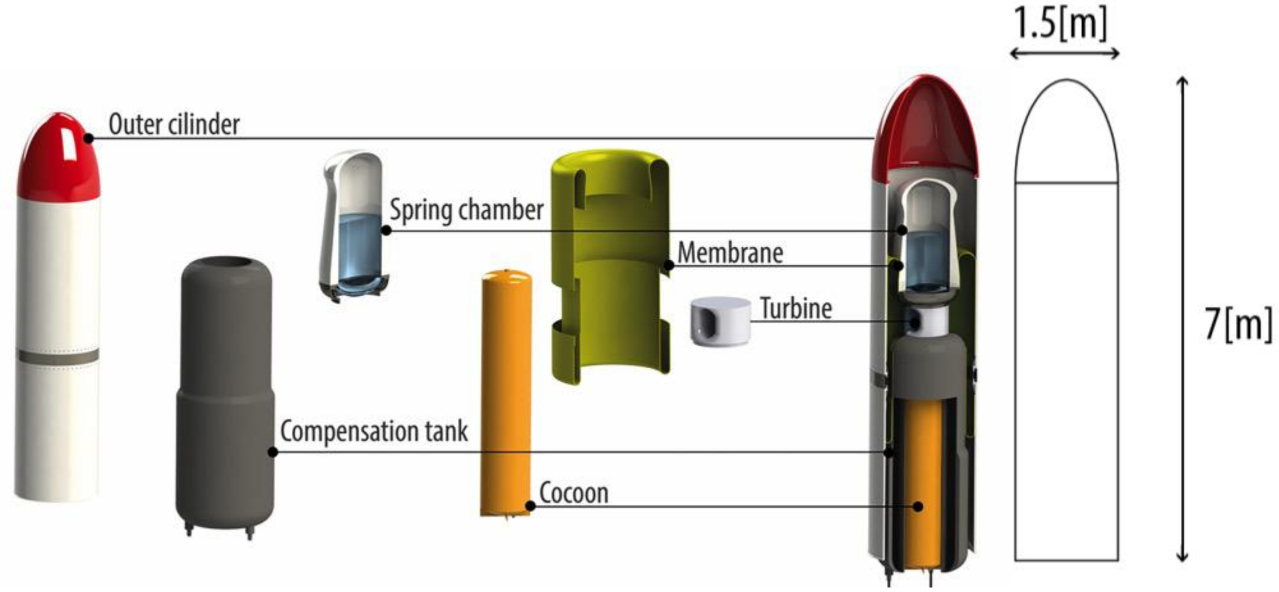


*Figure **Fout! Geen tekst met de opgegeven stijl in het document.**.1 : Exploded view Symphony*

The Symphony consists of two parts separated by a membrane. The hydrostatic pressure of passing waves pushes the upper part (Outer cylinder) down. This results in a decreasing inner volume of the Symphony. The decreasing volume creates an internal water flow through a turbine driving a generator. At the same time the inner pressure in the Spring Chamber builds up due to the decreasing volume. The counter movement, the Outer Cylinder moves up again, happens under a wave through as the inner pressure is larger than the hydrostatic pressure. The internal water flow is reversed through the turbine.

The membrane is the separation between the two parts of the Symphony. It acts as seal to enclose the inner pressure/volume and it acts as bearing for the cylinder. More precise the membrane is the variable volume 'breathing' under the waves. The inner volume changes due to the difference in the width in which the upper and lower part of the membrane roll up and down.

As the sleeve (outer cylinder) is being pushed down, the roll membrane starts to roll down. As the membrane rolls down the volume inside the membrane becomes less and forces the water into the spring room trough a turbine. As the build up pressure in the spring room forces the water back, it is pushed in the membrane which rolls up with the outer cylinder.

The total cycle is shown on the next page.

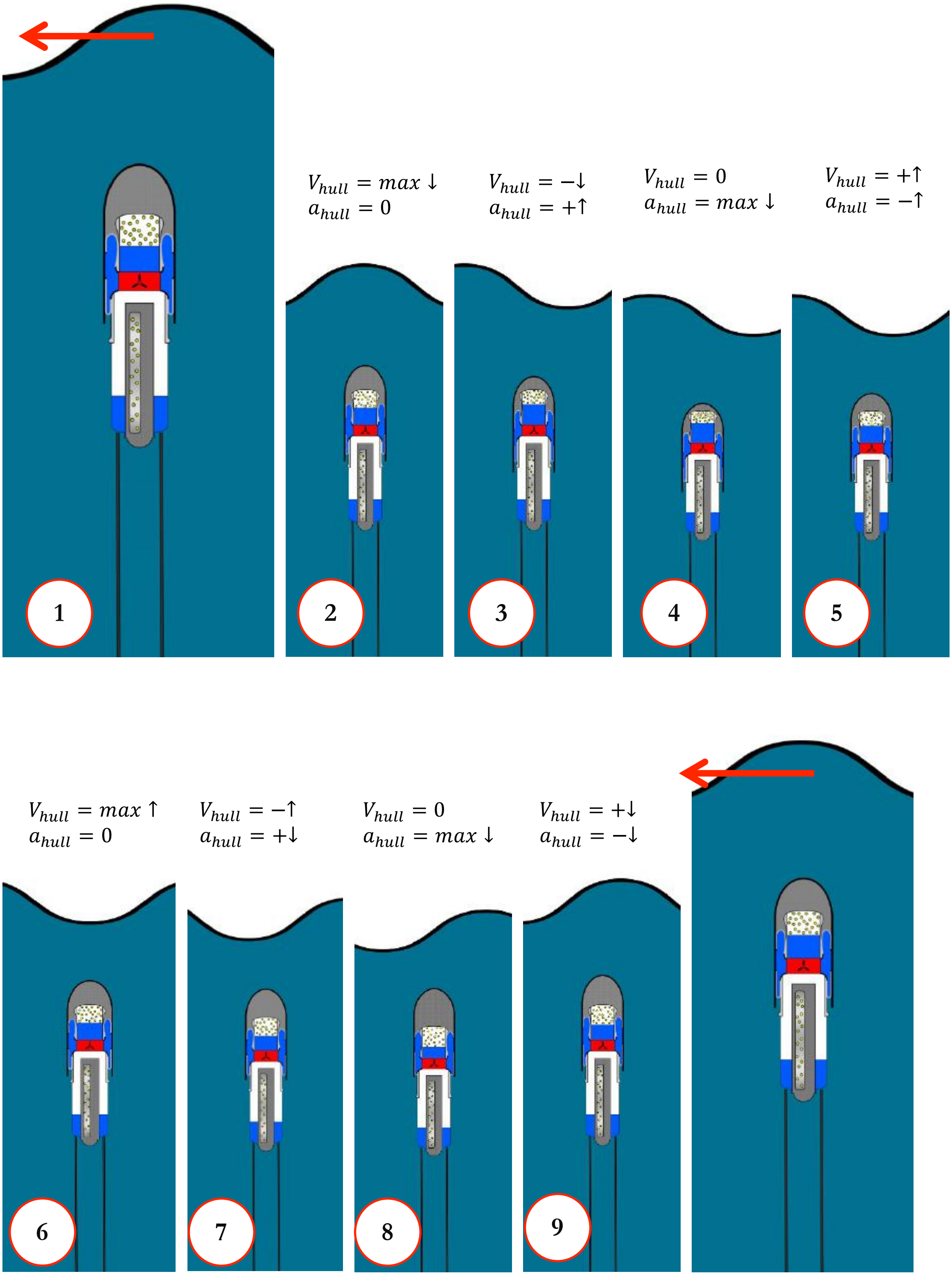


*Figure **Error! No text of specified style in document.**-1: Symphony cycle*

Membrane functions

Bearing

The membrane functions as a bearing in between de moving hull and the fixed compensation tank. It is important that the membrane centers the hull circumferentially to exclude possible collision between the hull and the compensation tank.

Sealing

The membrane acts as a sealing, protecting the internal components from the ocean water and preventing water to flow in the upper part of the hull.

End stop

The membrane will be used as an end stop. The end stop will be realised by narrowing the wall geometry.

Specifications

General specifications

Medium inside membrane	Water
Lower membrane external exposure	Ocean water
Upper membrane external exposure	Air(at with a relative vacuum of 80%)
Operational stroke (h)	2[m]
Full stroke (h)	4[m]

Load specifications

Operating pressure [P]	10-20 [Bar(o)]
Alternating cycles [n]	30.000.000 [cycles]
Lifetime [t]	10 [years]

Dimensions

Minimum span	75[mm]
Maximum span	+/- 210[mm]*

*The inside wall geometry acts as a negative spring that linearizes the airpsring. The membrane must be able to work properly at different dimensions since the dimensions of the geometry of the inside might be chanched due to optimalisation of the spring. The membrane should still be able to operate if the upper wall geometry changes by 20%.

Extra functions

Adjustable length

The inside wall geometry of the symphony is modular. After the Symphony is build, the wall geometry might be changed in order to make the system more efficient. If the inside wall geometry is changed the membrane will have more or less overspan in comparrison to the original state. The membrane will have a different touching surface. Herefore the membrane must be adjustable in length.

Spring stiffness

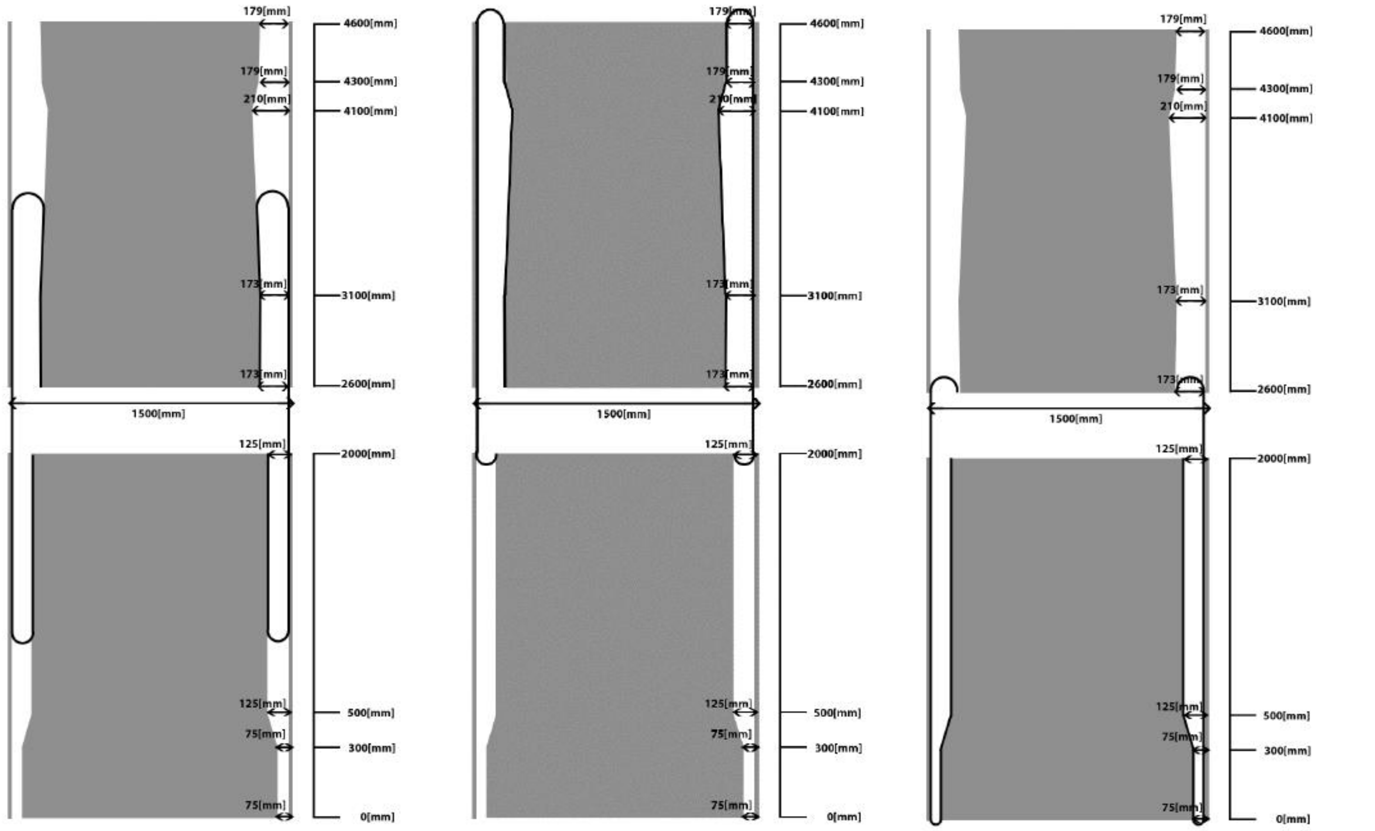
The airspring has an low spring stifness of around 800[n/m_{stroke}] If the membrane rolls along the surface the membrane's material will compress or expand.

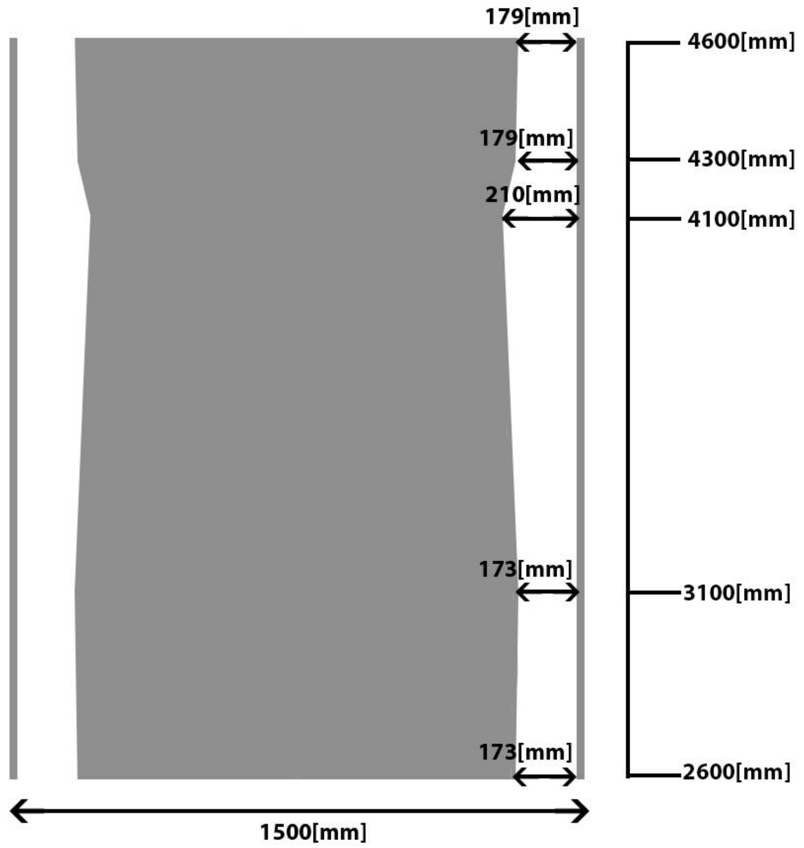
Demountable

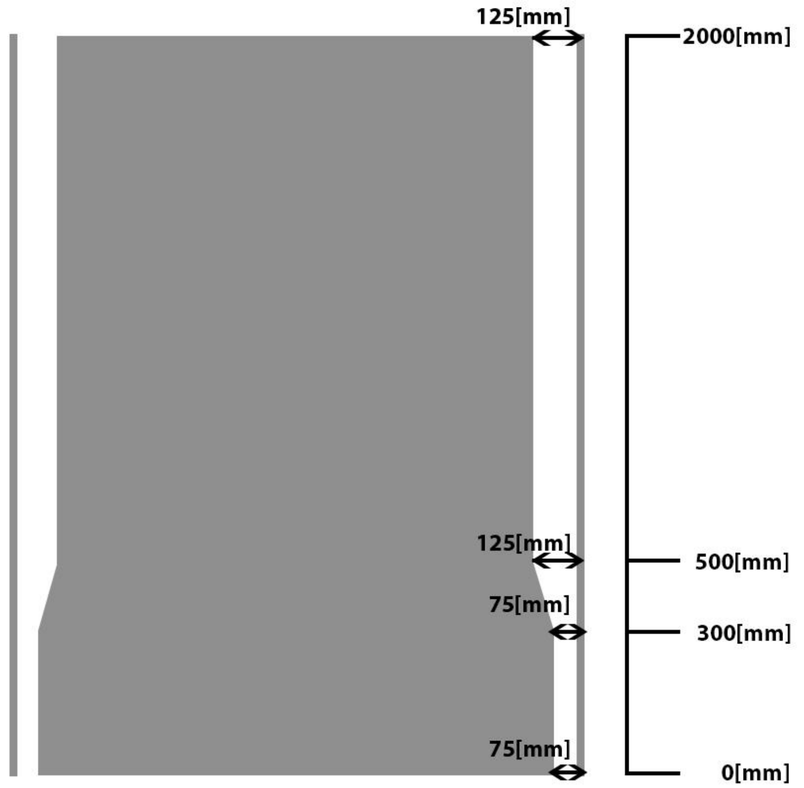
The membrane must be demountable for maintainance purposes.

Membrane dimensions

A picture of the membrane integrated in the Symphony Wave Power is shown in the figure bellow:




179[mm]
4600[mm]
179[mm]
4300[mm]
210[mm]
4100[mm]
173[mm]
3100[mm]
173[mm]
2600[mm]
1500[mm]


125[mm]
2000[mm]
125[mm]
500[mm]
75[mm]
300[mm]
75[mm]
0[mm]

Appendix 2: Membrane strength

TRELLEBORG

Report	TR ED-17-0016 Appendix 1	Subject	Calculation membrane strength
Date	14/013/2017	Product	Membrane
Revision	0	Project	WETFEET
Rev. date	26/01/2017	Customer	EC
File	\ED2017\ED-17-0016.xlsx	Cust ON	GA 641334
		TB ON	15-0019
By Checked	Dirk Jan van Waardhuizen	To	

Upper Membrane

Annulus	a =	**210**	[mm]			
Maximum deviation during operations	da =	**75**	[mm]			
Membrane thickness	tm =	**10**	[mm]			
Pressure	Pw =	**20**	[BAR]			
Diameter reinforcement	Rr =	**275**	[mm]			
Load design factor	γd =	**4**				
Wall design stress	Fw =	**1100**	[N/mm]			
Reinforcement D1000	Fr =	**1052**	[N/mm]			
No of layers	nr =	**2**				
Angle reinforcement	α =	**10**	[°]	=	**0.1745**	[RAD]
Axial available strength	Fra =	**2072**	[N/mm]			
Safety factor	γs =	**1.88**				

Lower Membrane

Annulus	a =	**125**	[mm]			
Membrane thickness	tm =	**10**	[mm]			
Maximum deviation during operations	da =	**75**	[mm]			
Pressure	Pw =	**20**	[BAR]			
Diameter reinforcement	Rr =	**190**	[mm]			
Load design factor	γd =	**4**				
Wall design stress	Fw =	**760**	[N/mm]			
Reinforcement D1000	Fr =	**1052**	[N/mm]			
No of layers	nr =	**2**				
Angle reinforcement	α =	**10**	[°]	=	**0.1745**	[RAD]
Axial available strength	Fra =	**2072**	[N/mm]			
Safety factor	γs =	**2.73**				

Appendix 3: Energy loss calculations

Report	TR ED-17-0016	Appendix 2	Subject	Calculation Roll off force & Energy loss
Date	14/01/2017		Product	Upper Membrane
Revision	0		Project	WETFEET
Rev. date	26/01/2017		Customer	EC GA
File	\ED2017\ED-17-0016.xlsx		Cust ON	641334
			TB ON	15-0019
By Checked	Dirk Jan van Waardhuizen		To	

Annulus	a =	191.5	[mm]		Hysteresis rubber	30.0%
Wall Thickness	tw =	10	[mm]			
Radius reinforcement	Rr =	90.75	[mm]			
Wall inner	ti =	5	[mm]			
Outside radius	Ro =	95.75	[mm]			
Inner radius	Ri =	85.75	[mm]			
Inner deformation	Ɛi =	0.06	σ i =	0.12	[Mpa]	
Outside deformation	Ɛo =	0.06	σ o =	0.12	[Mpa]	
Force	F =	0.60	[N/mm]			
Diameter	D =	1500	[mm]			
Circumference	O =	4712	[mm]			
Total bending force	Ftot =	2.82	[kN]			
Loss due to hysteresis	Floss =	0.85	[kN]			
Overall diameter						
Building diameter	Db =	1500	[mm]			
Internal diameter	Di =	1117	[mm]			
Compressive Strain	Ɛ =	-0.26				
Resulting stress	σ =	-0.78	[Mpa]			
Circumference	O =	4712	[mm]			
Force per unit	F =	-3.65	[kN/mm]			
Total Rubber thickness	tr =	10	[mm]			
Force	F =	-36.55	[kN]			
Loss due to hysteresis	Floss =	-10.96	[kN]			
Total loss due to hysteresis	Floss =	11.81	[kN]			
Travel	Le =	2000	[mm]			
Energy loss in membrane	E loss =	23.62	[kJ]			

Report	TR ED-17-0016	Appendix 2	Subject	Calculation Roll off force & Energy loss
Date	14/01/2017	TRELLEBORG	Product	Lower Membrane
Revision	0		Project	WETFEET
Rev. date	26/01/2017		Customer	EC GA
File	\ED2017\ED-17-0016.xlsx		Cust ON	641334
			TB ON	15-0019
By Checked	Dirk Jan van Waardhuizen		To	

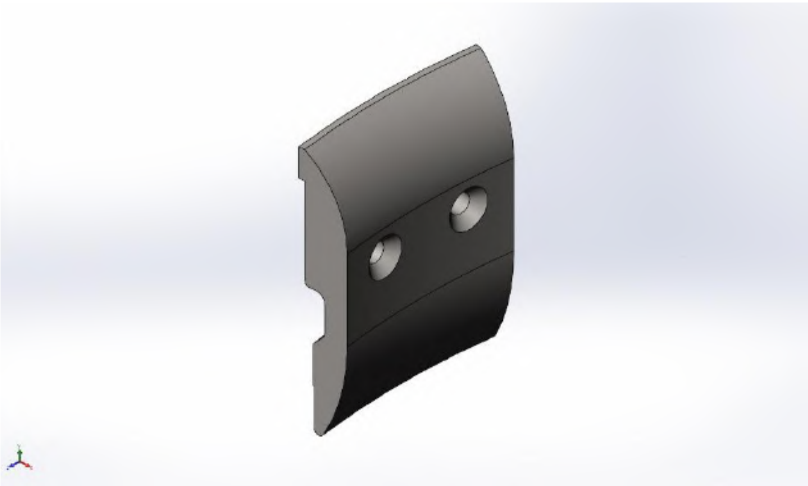
Annulus	a =	125	[mm]	Hysteresis rubber	30.0%	
Wall Thickness	tw =	10	[mm]			
Radius reinforcement	Rr =	57.5	[mm]			
Wall inner	ti =	5	[mm]			
Outside radius	Ro =	62.5	[mm]			
Inner radius	Ri =	52.5	[mm]			
Inner deformation	Ɛi =	0.09		σ i =	0.18	[Mpa]
Outside deformation	Ɛo =	0.09		σ o =	0.18	[Mpa]
Force	F =	0.91	[N/mm]			
Diameter	D =	1500	[mm]			
Circumference	O =	4712	[mm]			
Total bending force	Ftot =	4.31	[kN]			
Loss due to hysteresis	Floss =	1.29	[kN]			

Overall diameter

Building diameter	Db =	1500	[mm]
Internal diameter	Di =	1250	[mm]
Compressive Strain	Ɛ =	-0.17	
Resulting stress	σ =	-0.46	[Mpa]
Circumference	O =	4712	[mm]
Force per unit	F =	-2.17	[kN/mm]
Total Rubber thickness	tr =	10	[mm]
Force	F =	-21.69	[kN]
Loss due to hysteresis	Floss =	-6.51	[kN]
Total loss due to hysteresis	Floss =	7.80	[kN]
Travel	Le =	2000	[mm]
Energy loss in membrane	E loss =	15.60	[kJ]

Appendix 4: FEA Upper membrane outer clamping plate – example of FEA work performed

Trelleborg Ridderkerk **ED-17-0016 Appendix 4**



ED-17-0016 Appendix 4 Simulation of Clamping Plate Inner Upper R750

Date : 25 January 2017
Designer : DJDvW
Study name : Static 1
Analysis type : Static

Table of Contents

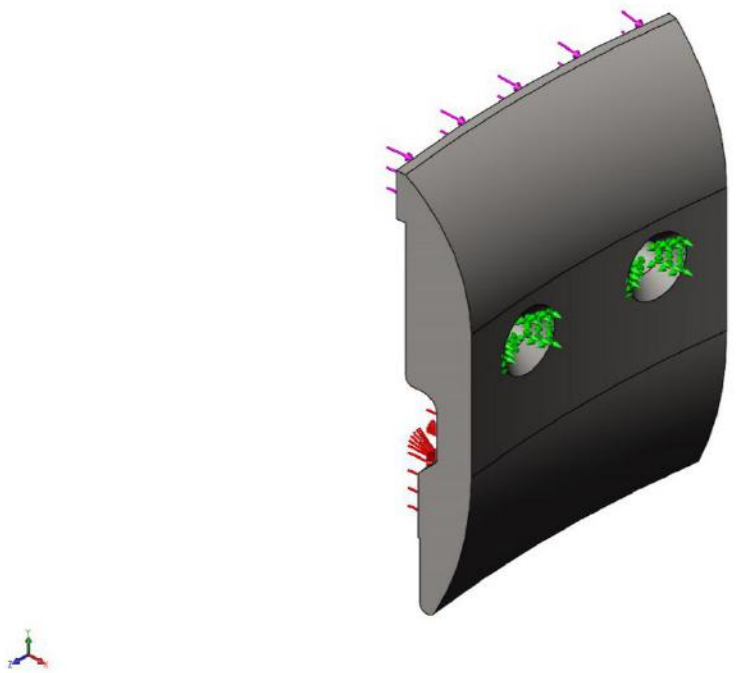
Description

WETFEET project Deliverable D3.7
FEA on Upper R750 clamping plate

Assumptions

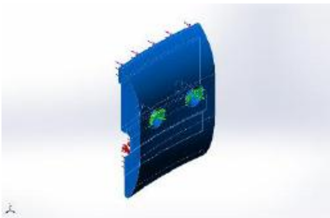
Bolt holes are fixed

Model Information



Model name: Klemplaat buiten R750 - BOVEN-A
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Fillet3 	Solid Body	**Mass:11.4066 kg** **Volume:0.00146238 m^3** **Density:7800 kg/m^3** **Weight:111.785 N**	**W:\Project\2015\15-0019 WEC Wetfeet - EC subsidised\04 - Design\5 - Clamping\Klemplaat buiten R750 - BOVEN-A.SLDPRT** Jan 25 10:37:15 2017

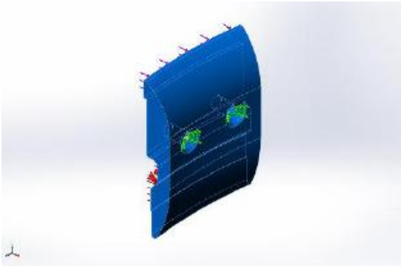
Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (W:\Project\2015\15-0019 WEC Wetfeet - EC subsidised\04 - Design\5 - Clamping)

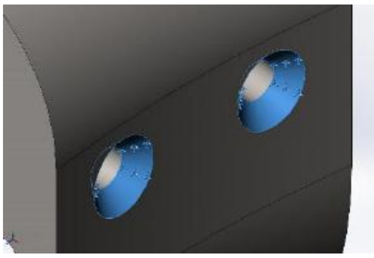
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

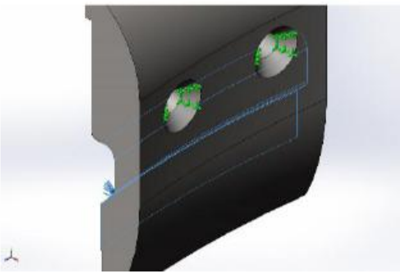
Model Reference	Properties	Components
	**Name:** 1.0570 (S355J2G3) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Max von Mises Stress **Yield strength:** 3.15e+008 N/m^2 **Tensile strength:** 4.9e+008 N/m^2 **Elastic modulus:** 2.1e+011 N/m^2 **Poisson's ratio:** 0.28 **Mass density:** 7800 kg/m^3 **Shear modulus:** 7.9e+010 N/m^2 **Thermal expansion coefficient:** 1.1e-005 /Kelvin	SolidBody 1(Fillet3)(Klemplaat buiten R750 - BOVEN-A)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** 2 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-156029	1516.91	-3.56348	156036
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		**Entities:** 1 face(s) **Type:** Apply normal force **Value:** 82500 N
Pressure-1		**Entities:** 6 face(s) **Type:** Normal to selected face **Value:** 4.2e+006 **Units:** N/m^2 **Phase Angle:** 0 **Units:** deg

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	10.8144 mm
Tolerance	0.540721 mm
Mesh Quality Plot	High

Mesh information - Details

Total Nodes	14583
Total Elements	8959
Maximum Aspect Ratio	13.753
% of elements with Aspect Ratio < 3	97.7
% of elements with Aspect Ratio > 10	0.603
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:01
Computer name:	TESRIDL032

Resultant Forces

Reaction forces

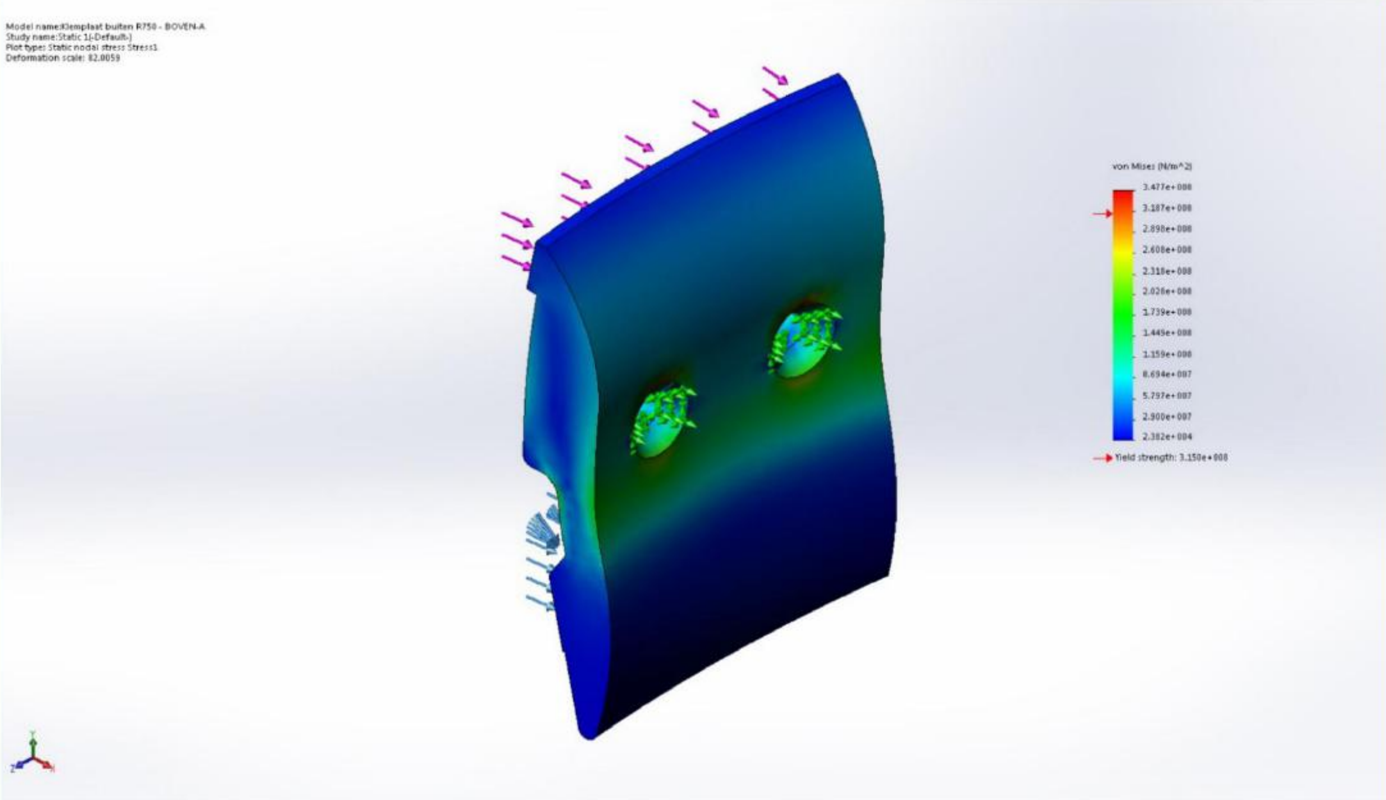
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-156029	1516.91	-3.56348	156036

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

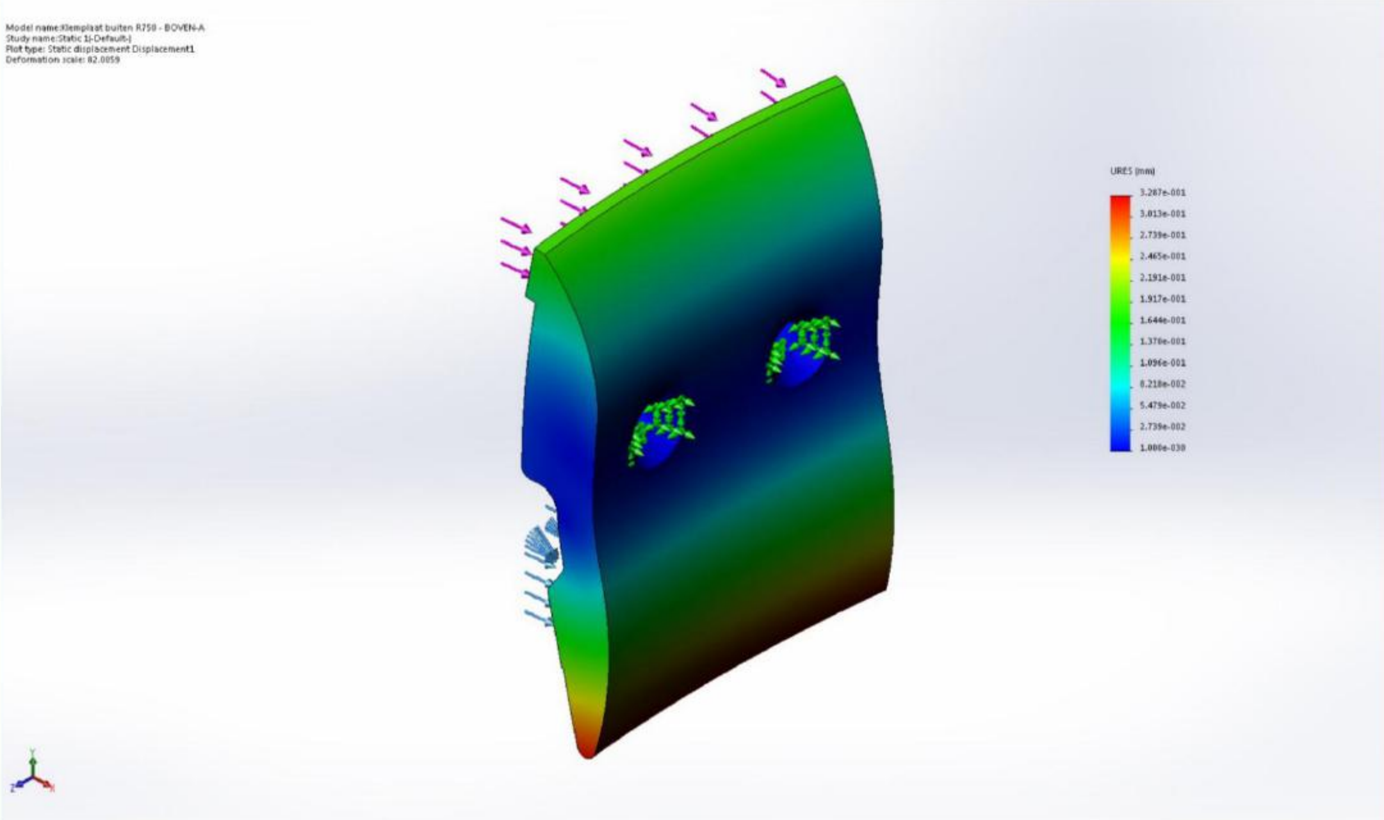
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.382e+004N/m^2 Node: 14286	3.477e+008N/m^2 Node: 309



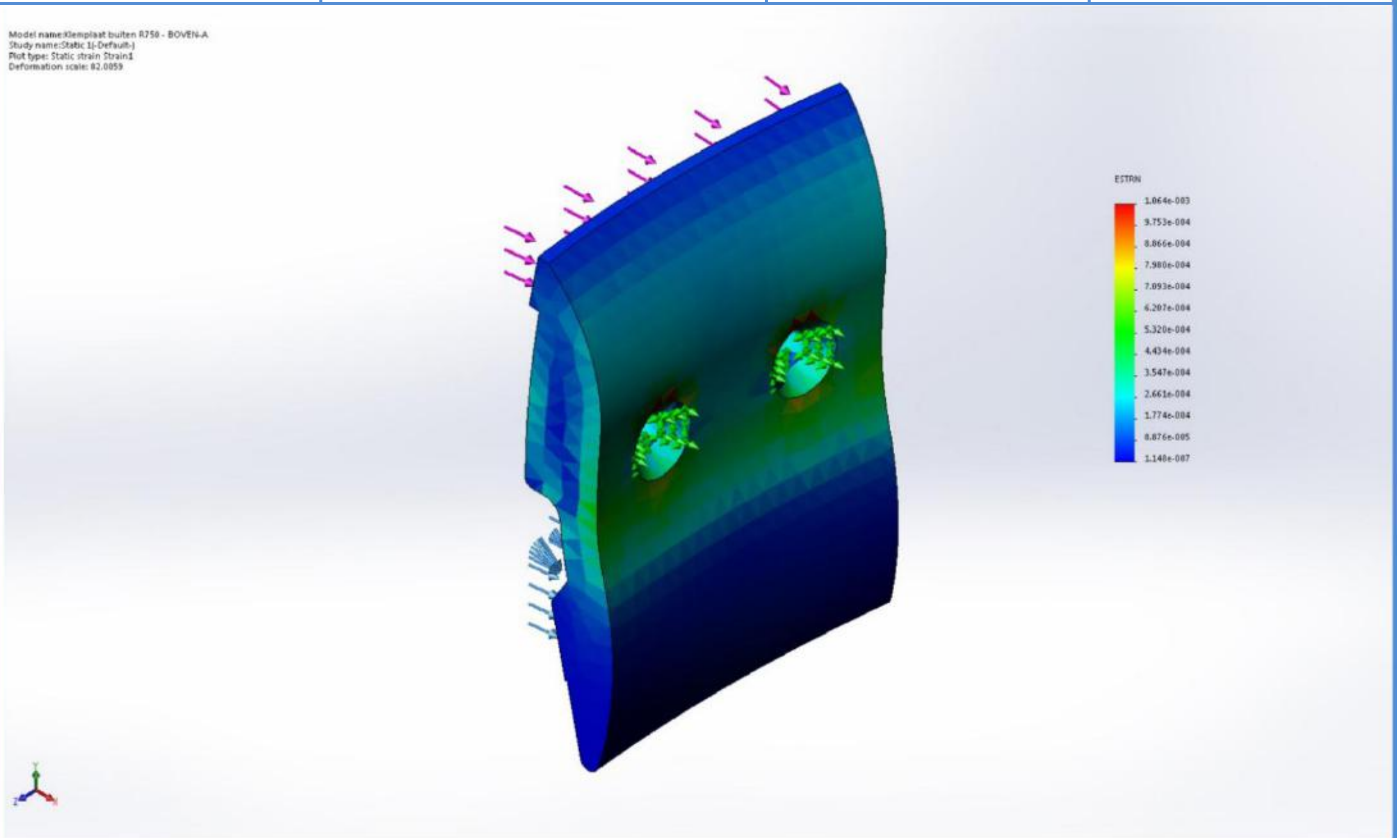
Klemplaat buiten R750 - BOVEN-A-Static 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+000mm Node: 1	3.287e-001mm Node: 14223



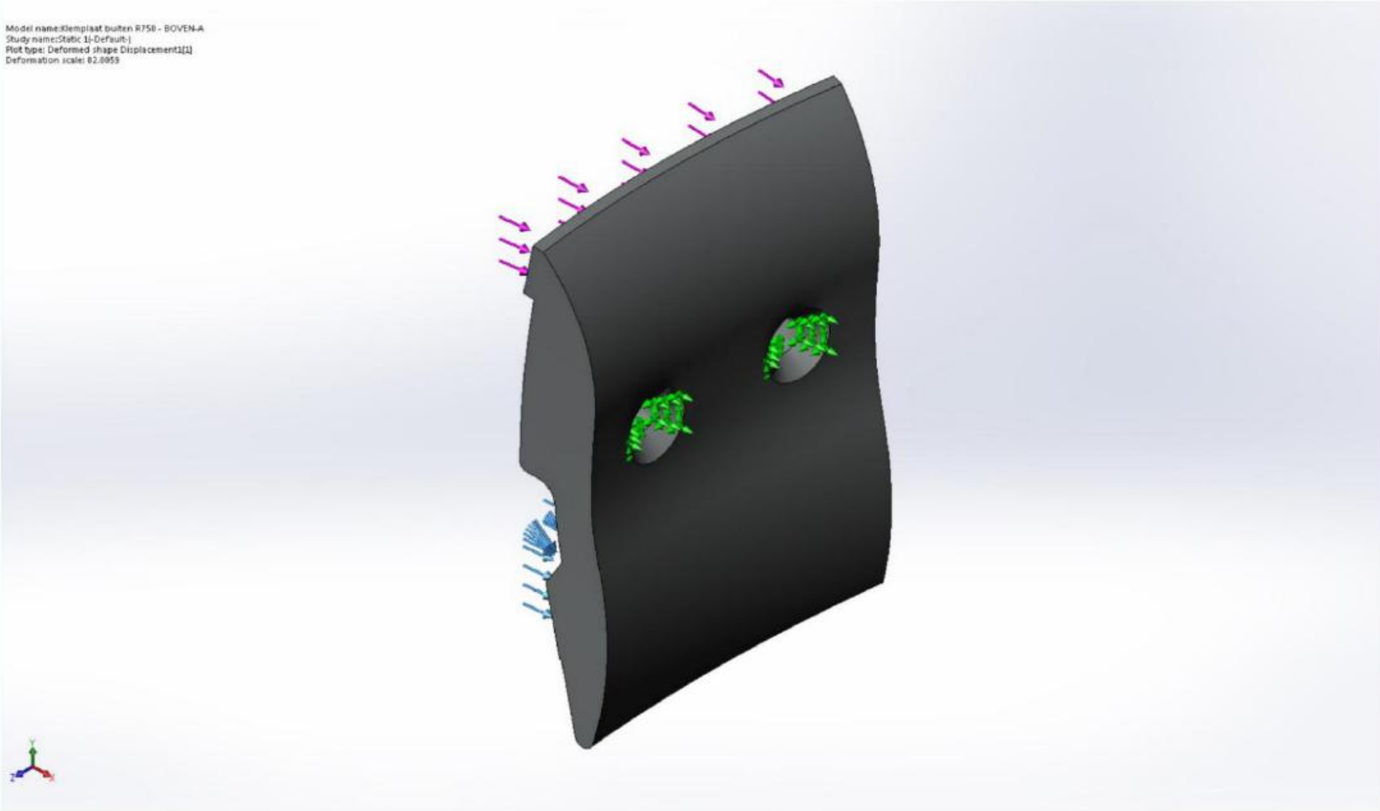
Klemplaat buiten R750 - BOVEN-A-Static 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.148e-007 Element: 2386	1.064e-003 Element: 5652



Klemplaat buiten R750 - BOVEN-A-Static 1-Strain-Strain1

Name	Type
Displacement1{1}	Deformed shape



Klemplaat buiten R750 - BOVEN-A-Static 1-Displacement-Displacement1{1}

Conclusion

Stresses and strains stay within the material limitations

Appendix 5: FEA membrane

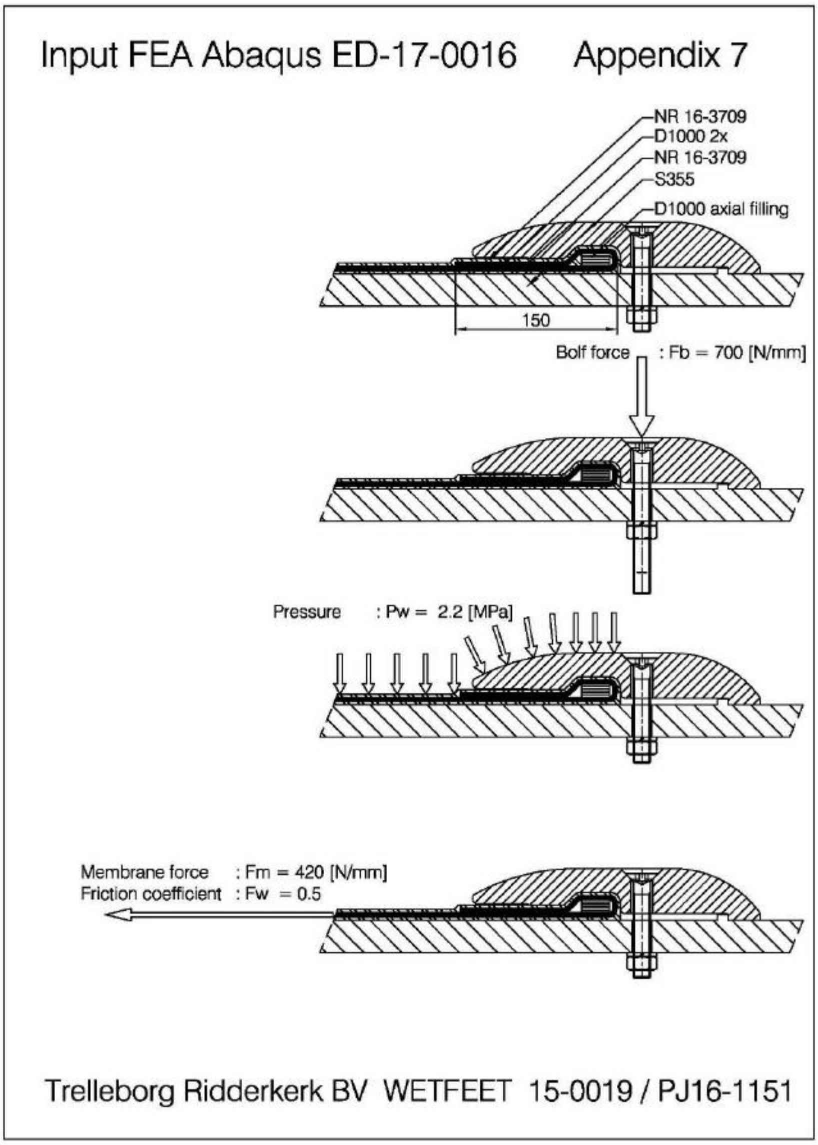
Trelleborg Ridderkerk BV

Report	: TR ED 2017-0016	Subject	: FEA using ABAQUS
Date	: 25-01-2017	Product	: Reinforced Rubber membrane
Appendix	: 7		

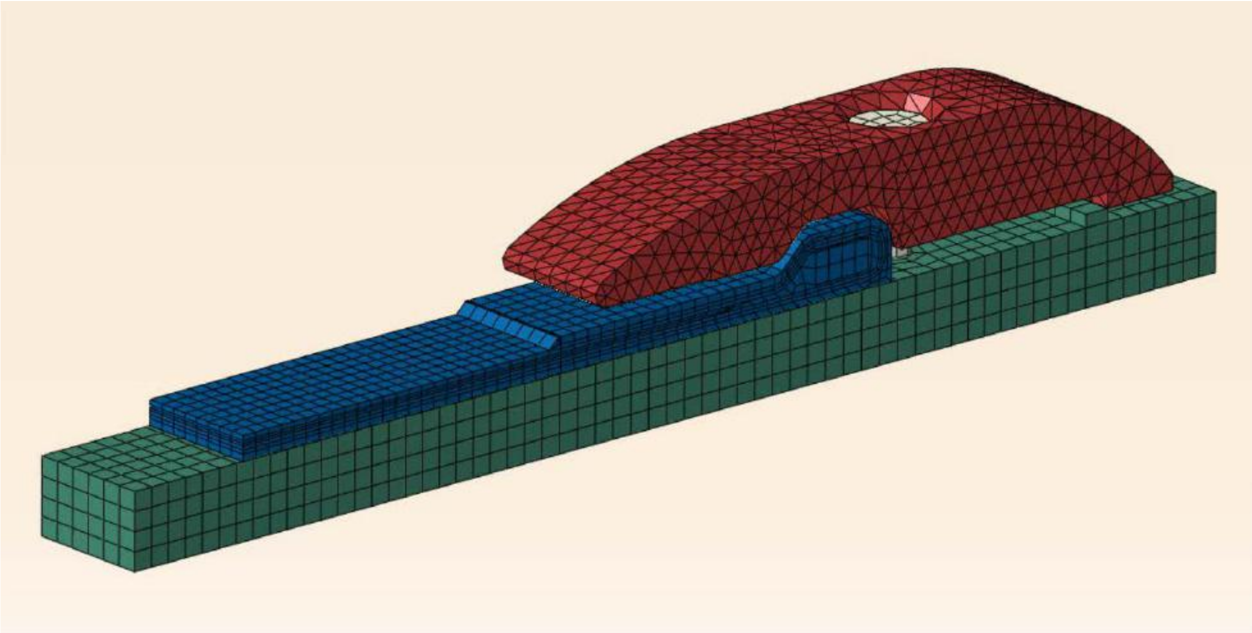
1] Input FEA

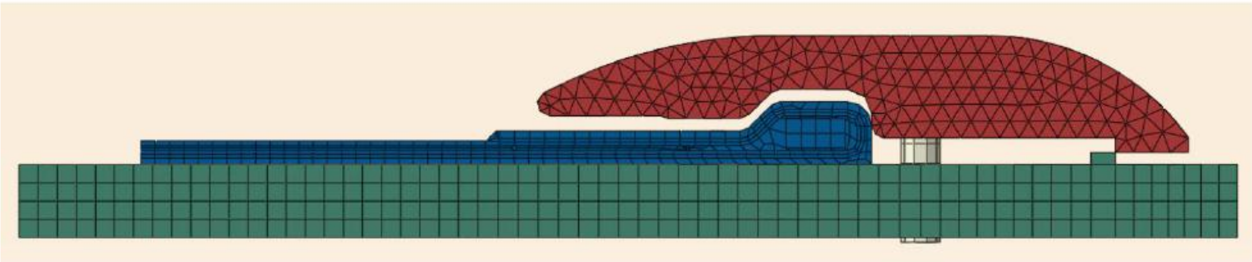
The FEA analysis for the WETFEET project is carried out using ABAQUS non linea solver. A small part of the membrane was modeled to study the stresses in the calmping area of the membrane.

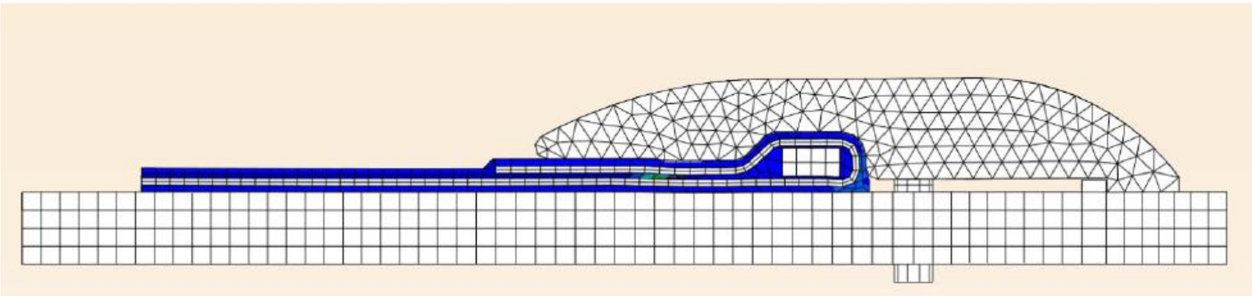
Input according to below picture

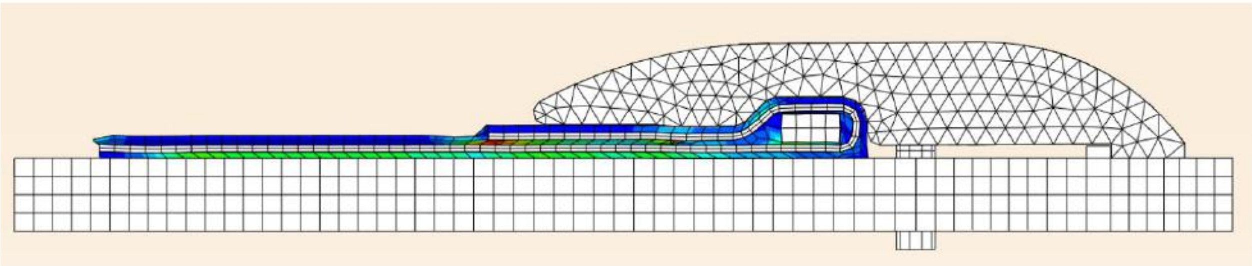


The input resulted in the models as shown below









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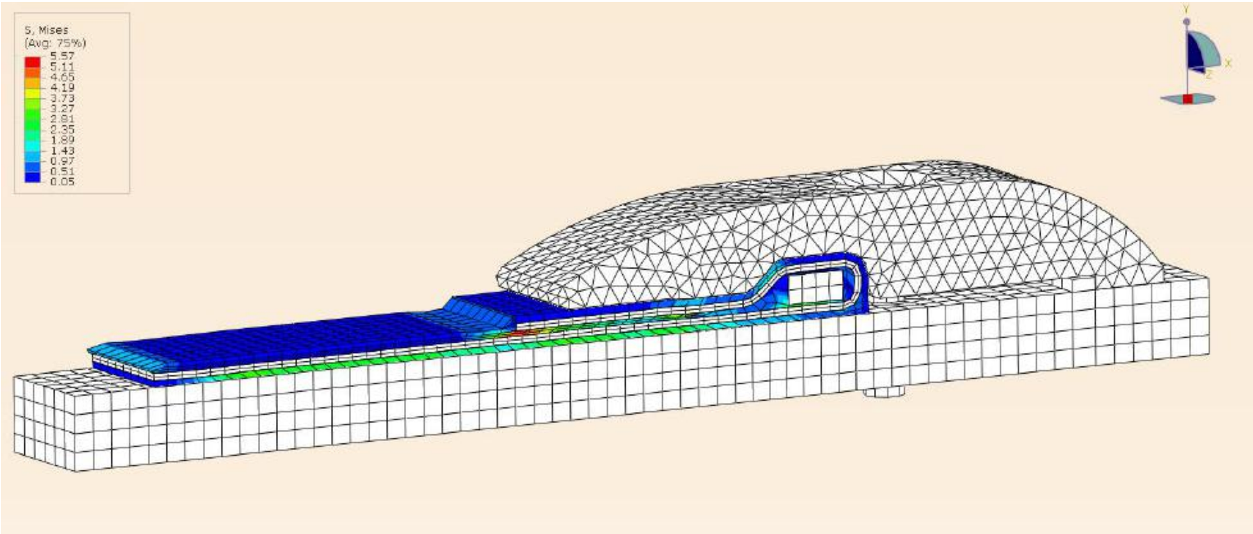
2] Results

FEM Clamping WETFEET



Simulation consists of 4 steps
1) Clamping by bolt movement
2) Pressure of 2.2 MPa
3) Pulling reinforcement
Global friction 0.5
VMises stresses shown at final step. Steelwork and reinforcement not included in stress analysis.

The stresses and strains are within the limitations of the rubber used.

Appendix 6: Loss of membrane 3500mm

Report	TR ED-17-0016 Appendix 6	Subject	Calculation Roll off force & Energy loss
Date	14/01/2017	Product	Upper Membrane
Revision	0	Project	WETFEET
Rev. date	26/01/2017	Customer	EC GA
File	\ED2017\ED-17-0016.xlsx	Cust ON	641334
		TB ON	15-0019
By	Dirk Jan van Waardhuizen	To	

Annulus	a =	191.5	[mm]		Hysteresis rubber	30.0%	
Wall Thickness	tw =	10	[mm]				
Radius reinforcement	Rr =	90.75	[mm]				
Wall inner	ti =	5	[mm]				
Outside radius	Ro =	95.75	[mm]				
Inner radius	Ri =	85.75	[mm]				
Inner deformation	Ɛi =	0.06		σ i =	0.12	[Mpa]	
Outside deformation	Ɛo =	0.06		σ o =	0.12	[Mpa]	
Force	F =	0.60	[N/mm]				
Diameter	D =	3500	[mm]				
Circumference	O =	10996	[mm]				
Total bending force	Ftot =	6.59	[kN]				
Loss due to hysteresis	Floss =	1.98	[kN]				
Overall diameter							
Building diameter	Db =	3500	[mm]				
Internal diameter	Di =	3117	[mm]				
Compressive Strain	Ɛ =	-0.11					
Resulting stress	σ =	-0.28	[Mpa]				
Circumference	O =	10996	[mm]				
Force per unit	F =	-3.12	[kN/mm]				
Total Rubber thickness	tr =	10	[mm]				
Force	F =	-31.24	[kN]				
Loss due to hysteresis	Floss =	-9.37	[kN]				
Total loss due to hysteresis	Floss =	11.35	[kN]				
Travel	Le =	2000	[mm]				
Energy loss in membrane	E loss =	22.70	[kJ]				

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Report	TR ED-17-0016 Appendix 8	Subject	Calculation Roll off force & Energy loss
Date	14/01/2017	Product	Lower Membrane
Revision	0	Project	WETFEET
Rev. date	26/01/2017	Customer	EC GA
File	\ED2017\ED-17-0016.xlsx	Cust ON	641334
		TB ON	15-0019
By	Dirk Jan van Waardhuizen	To	

Annulus	a =	125	[mm]	Hysteresis rubber	30.0%	
Wall Thickness	tw =	10	[mm]			
Radius reinforcement	Rr =	**57.5**	[mm]			
Wall inner	ti =	**5**	[mm]			
Outside radius	Ro =	**62.5**	[mm]			
Inner radius	Ri =	**52.5**	[mm]			
Inner deformation	Ɛi =	**0.09**		σ i =	**0.18**	[Mpa]
Outside deformation	Ɛo =	**0.09**		σ o =	**0.18**	[Mpa]
Force	F =	**0.91**	[N/mm]			
Diameter	D =	3500	[mm]			
Circumference	O =	**10996**	[mm]			
Total bending force	Ftot =	**10.06**	[kN]			
Loss due to hysteresis	Floss =	**3.02**	[kN]			
Overall diameter						
Building diameter	Db =	3500	[mm]			
Internal diameter	Di =	3250	[mm]			
Compressive Strain	Ɛ =	**-0.07**				
Resulting stress	σ =	**-0.18**	[Mpa]			
Circumference	O =	**10996**	[mm]			
Force per unit	F =	**-1.96**	[kN/mm]			
Total Rubber thickness	tr =	**10**	[mm]			
Force	F =	**-19.58**	[kN]			
Loss due to hysteresis	Floss =	**-5.87**	[kN]			
Total loss due to hysteresis	Floss =	**8.89**	[kN]			
Travel	Le =	2000	[mm]			
Energy loss in membrane	E loss =	**17.78**	[kJ]			

Appendix 7: Loss of membrane 6000mm

Report	TR ED-17-0016	Appendix 9	Subject	Calculation Roll off force & Energy loss
Date	14/01/2017		Product	Upper Membrane
Revision	0		Project	WETFEET
Rev. date	27/02/2017		Customer	EC GA
File	\ED2017\ED-17-0016.xlsx		Cust ON	641334
			TB ON	15-0019
By	Dirk Jan van Waardhuizen		To	

Annulus	a =	191.5	[mm]		Hysteresis rubber	30.0%
Wall Thickness	tw =	10	[mm]			
Radius reinforcement	Rr =	90.75	[mm]			
Wall inner	ti =	5	[mm]			
Outside radius	Ro =	95.75	[mm]			
Inner radius	Ri =	85.75	[mm]			
Inner deformation	Ɛi =	0.06		σ i =	0.12	[Mpa]
Outside deformation	Ɛo =	0.06		σ o =	0.12	[Mpa]
Force	F =	0.60	[N/mm]			
Diameter	D =	6000	[mm]			
Circumference	O =	18850	[mm]			
Total bending force	Ftot =	11.30	[kN]			
Loss due to hysteresis	Floss =	3.39	[kN]			
Overall diameter						
Building diameter	Db =	6000	[mm]			
Internal diameter	Di =	5617	[mm]			
Compressive Strain	Ɛ =	-0.06				
Resulting stress	σ =	-0.16	[Mpa]			
Circumference	O =	18850	[mm]			
Force per unit	F =	-2.97	[kN/mm]			
Total Rubber thickness	tr =	10	[mm]			
Force	F =	-29.75	[kN]			
Loss due to hysteresis	Floss =	-8.92	[kN]			
Total loss due to hysteresis	Floss =	12.31	[kN]			
Travel	Le =	2000	[mm]			
Energy loss in membrane	E loss =	24.63	[kJ]			

Report	TR ED-17-0016 Appendix 9	Subject	Calculation Roll off force & Energy loss
Date	14/01/2017	Product	Lower Membrane
Revision	0	Project	WETFEET
Rev. date	27/02/2017	Customer	EC GA
File	\ED2017\ED-17-0016.xlsx	Cust ON	641334
		TB ON	15-0019
By	Dirk Jan van Waardhuizen	To	

Annulus	a =	125	[mm]		Hysteresis rubber	30.0%
Wall Thickness	tw =	10	[mm]			
Radius reinforcement	Rr =	57.5	[mm]			
Wall inner	ti =	5	[mm]			
Outside radius	Ro =	62.5	[mm]			
Inner radius	Ri =	52.5	[mm]			
Inner deformation	Ɛi =	0.09	σ i =	0.18	[Mpa]	
Outside deformation	Ɛo =	0.09	σ o =	0.18	[Mpa]	
Force	F =	0.91	[N/mm]			
Diameter	D =	6000	[mm]			
Circumference	O =	18850	[mm]			
Total bending force	Ftot =	17.24	[kN]			
Loss due to hysteresis	Floss =	5.17	[kN]			

Overall diameter

Building diameter	Db =	6000	[mm]
Internal diameter	Di =	5750	[mm]
Compressive Strain	Ɛ =	-0.04	
Resulting stress	σ =	-0.10	[Mpa]
Circumference	O =	18850	[mm]
Force per unit	F =	-1.90	[kN/mm]
Total Rubber thickness	tr =	10	[mm]
Force	F =	-18.96	[kN]
Loss due to hysteresis	Floss =	-5.69	[kN]
Total loss due to hysteresis	Floss =	10.86	[kN]
Travel	Le =	2000	[mm]
Energy loss in membrane	E loss =	21.72	[kJ]

Appendix 8: Challenges for full scale deployment

Trelleborg Ridderkerk BV

Report	: TR ED 2017-0016	Subject	: Challenges for full scale production
Date	: 04-04-2017	Product	: Symphony Structural Membrane
Appendix	: 10		

Below table shows the challenges to be solved in case of large scale production and possible solutions

Dimensions [mm]	Symphony 1 pc / week	Measures/ solutions	Symphony 2 pcs / week	Measures/ solutions
Ø1500	Capacity of building tool compared to building hours required	Additional Tool required	Capacity of building tools compared to building hours required	Additional Tools required
Ø3500	Challenging are the design and the dimensions of the building Tool	Technically feasible requires design and production time	Capacity of building tools compared to building hours required	Increase number of Tools
Ø6000	1] Challenging are the design and the dimensions of the building Tool	Technically feasible requires design and production time	1] Challenging are the design and the dimensions of the building Tool	Increase number of Tools
	2] Also challenging is the vulcanisation system to be applied to the tool	Technically feasible requires design and production time	2] Also challenging is the vulcanisation system to be applied to the tools	Technically feasible requires design and production time
	3] Find a proper location	To be adressed when there is an actual requirement	3] Find a proper location	To be adressed when there is an actual requirement
	4] Time frame needed to accomplish 1] to 3]	To be adressed when there is an actual requirement	4] Time frame needed to accomplish 1] to 3]	To be adressed when there is an actual requirement