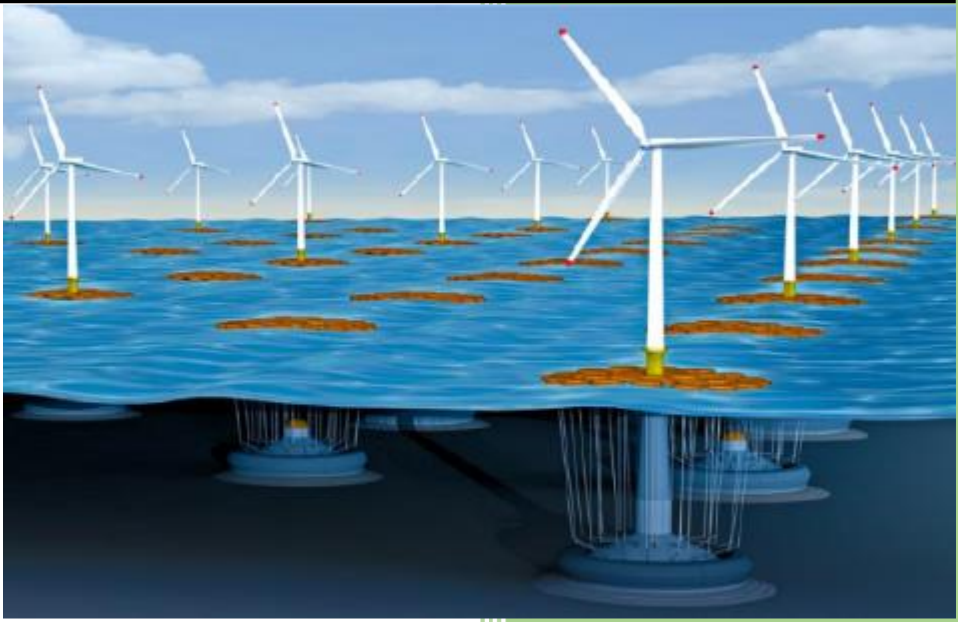
Fold Structure Detection Analysis during Inflation and Deflation Process on Bladder Reservoir of Ocean Grazer using 3D Finite Element Method



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OCEAN GRAZER

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Abstract

The world's needs of green energy have become more prominent in recent years due to the global commitment of limiting carbon emission in the coming decades. While carbon-based fuels remain one of the major energy sources in the world, recent technological advances in renewable energy sources have offered promising low-cost alternative to carbon-based energy sources. Ocean Grazer is one of the new green energy. It is an offshore hybrid energy harvester that combines wind power, wave movement, and hydrostatic pressure to transform it into electricity power. The bladder reservoir is one of the Ocean Grazer sub-systems, the so-called Ocean Battery systems, which operates as an energy storage on the bottom of the sea and be an energy storage by using hydrostatic pressure of seawater. Due to the presence of folds of bladder reservoir in the first Ocean Battery's design experimental lab test, a new design has been proposed to minimize the fold structure along the membrane because folds can shorten the lifetime of part. However, it is still not yet known what type of the simulation method for fold detection analysis before doing an experimental study. Therefore, the aim of study is to define what method that is suitable for fold detection simulation and to determine whether the new bladder reservoir design has fewer folds than the first one. To address the first question, we adopt the simulation method from the analysis of parts in another similar application that exhibits the same behaviour and has been experimentally validated. We first validate the existing fold detection method to the first bladder reservoir design based on the available experimental data. Subsequently, the new bladder design was analyzed using the method and get the result.

Acknowledgement

After doing 6 months struggle to do the research, finally I can present the thesis, "Fold Structure Detection Analysis during Inflation and Deflation Process on Bladder Reservoir of Ocean Grazer using 3D Finite Element Method". This research is performed as the mandatory course for Industrial Engineering and Management at University of Groningen. During the period of working on this, I learned a lot by facing a lot of the obstacles and find the opportunities to solve and finish the project.

First, I would like to thank you to Indonesian Endownment Fund for Education (LPDP) for financially supporting my study at University of Groningen. Second, I want to thank you to my parents, Lilih Dwi Priyanto and Ruliasih, because they are the most supportive system during my study and they are the one who always push me to keep learn a lot when I already comfortable with my job. Third, a sincere appreciation to my grandmothers, Wasini and Suprihatin, who always remind me that far from home is not a big problem if there is an opportunity, although they were already passed away when I am doing my study here and I couldn't bring them to the graveyard. Fourth, a sincere appreciation also for my wife, Famelia Nurlaela, who always stay besides me even though she also doing her PhD. Fifth, I also want to thank you to my older brother, Anindito Kusumojati, who open my eyes and be my role model since he started first to get a master scholarship in Delft before me. Then in the university, I would like to thank you to both of my supervisor, Prof. Bayu Jayawardhana and my second assessor Prof. Antonis Vakis who always support me not only in the research, but also my personal problem during my study. Last, I would say thank all my friends in Groningen, my Indonesian friends (PPI Groningen), and Ocean Grazer research group.

I hope this research can be useful for other people who are looking for the appropriate method for bladder reservoir analysis.

Adityo Kuncorojati

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Chapter 1

Introduction

Every year, the increasing of energy consumption over the world is not balanced with the usage of renewable resource as for the energy production because based on BP Statistical Review of World Energy, the energy resource is still dominated by coal as can be seen on Figure 1.1 (BP, 2018). Government of many countries are become more serious to limit their gas emission that is produced from many activities in their countries such as industry, transportation, and energy production. In the energy production sector, according to the International Energy Agency, a third of the CO_2 emissions in the world comes from coal-fired power plants. However, most of countries electricity production is really dependent on this type of energy (United Nations, 2018). Therefore, a new method of energy production which use renewable resource and has more friendly to the environment are needed.

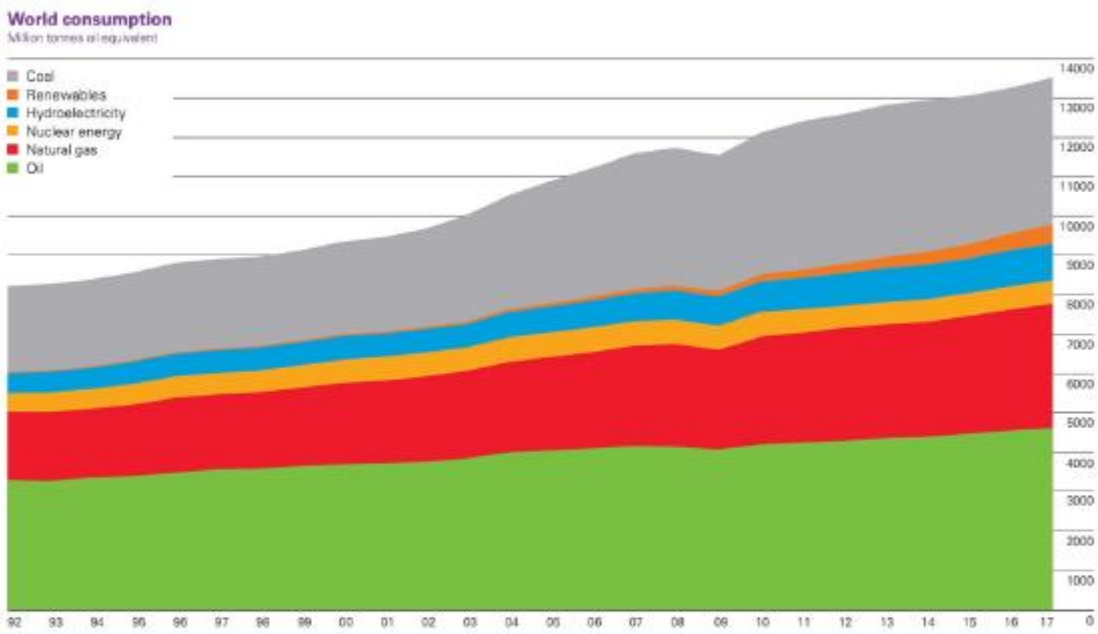

Figure 1. 1: World energy consumption in million tonnes of oil, from 1992 to 2017. Retrieved from (BP, 2018)

Ocean Grazer is one of the latest developments from researchers of Engineering and Technology at University of Groningen which focus on renewable energy production and storage system. The Ocean Grazer device is designed to harvest and store renewable energy from multiple sources in the ocean. It is designed to be modular in order to harvest renewable energy from wind, wave and solar in the ocean and to store them locally. The storage capability allows it to smoothen the energy intermittency as well as to guarantee a constant level of electrical energy production. The latter has recently been recognized as a crucial technology for the integration of large-scale renewable energy into the existing mixed electrical grid (Ocean Grazer, 2018). Ocean grazer consist of three main parts which is wind turbine, floater blanket, and reservoir as shown on Figure 1.2. The wind turbine is purposed to convert mechanical energy from wind blade rotation into electrical energy by using a turbine. The floater blanket produce energy by a connection to the pump and using wave movement to push the pump. The last main part of the Ocean Grazer is the reservoir that located on the bottom of the sea. It uses a bladder system which inflates and deflates continuously by using inner pump and outer hydrostatic pressure, then the water from bladder will be used to drive the turbine for electrical energy generation (Ocean Grazer, 2018).

Figure 1. 2: The Ocean Grazer. Retrieved from (Prins et al., 2017).

According to the previous bladder design by Sietse van den Elzen (2018) and evaluated by J.A. Koning (2018) as shown on Figure 1.3. From those researches, it claims that there was no fold structure in the membrane based on cross-sectional dimension and stress concentration only happen near the join with the rigid body because its sharp angle, as shown on Figure 1.4.

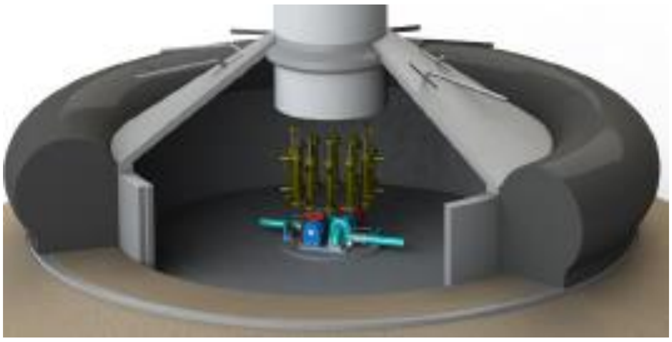

Figure 1. 3: Bladder reservoir design. Retrieved from (Koning, 2018)

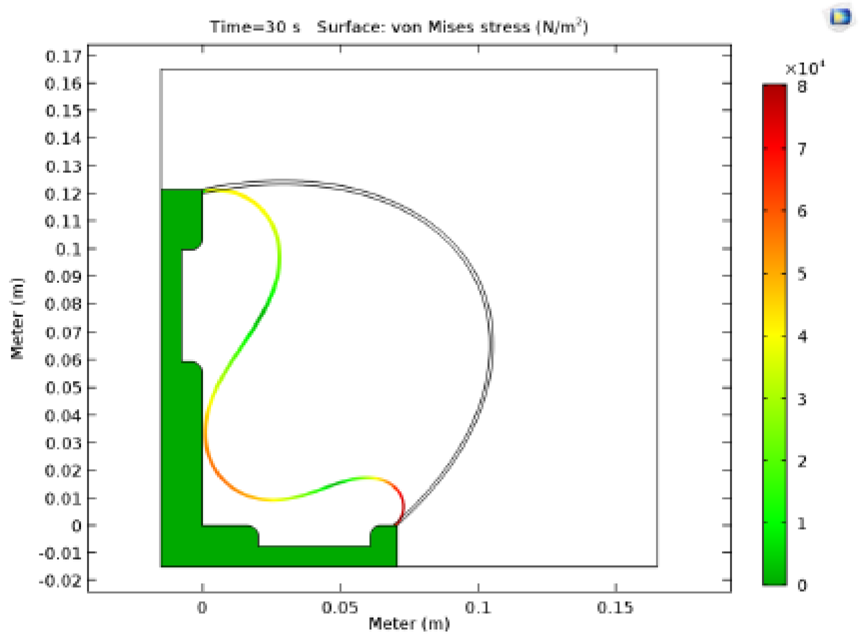

Figure 1. 4: Stress analysis simulation when bladder reservoir deflates. Retrieved from (Koning, 2018)

However, in the research from C.B. van den Hoek (2019) which validated the concept using principles of photogrammetry as the approach, the bladder has different behaviour. Then it also in line with experimental study from Ocean Grazer itself that the rubber membrane has fold structure in fully deflated condition which fold is happened because the length of rubber membrane in circular direction is longer than the length of rigid body surface as can be seen as can be seen on Figure 1.5. This phenomenon is forcing the material to be fully folded and lead to shorten life time of the rubber. Therefore, the goal of this research is to determine the new design of the bladder reservoir which has lower folded material when the reservoir is fully deflates.

Figure 1. 5: Bladder reservoir in fully deflates condition. Retrieved from (Ocean Grazer, 2018)

This research is based on the Ocean Grazer BV problem and plan about their bladder reservoir because they plan to increase the TRL (Technology Readiness Level) therefore, they can make a prototype test in Wadden Sea. TRL is used to indicates the development level of technology to be ready for realizing as shown in Figure 1.6 (Mankins, 1995). The prototype must have a minimum some specific requirements to reach an enough TRL level for making a reliable model to be tested and it should have a long life time which can be reached by minimizing the fold.

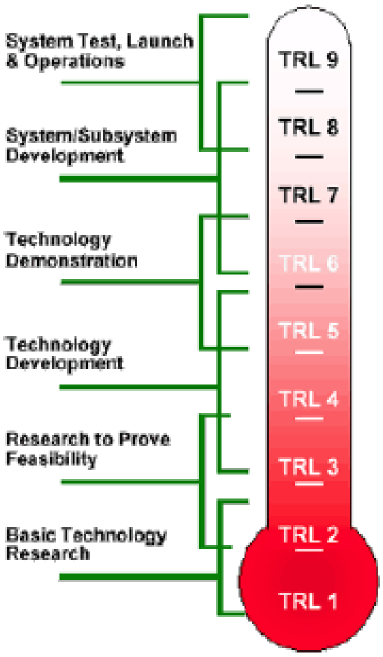

Figure 1. 6: Technology Readiness Levels. Retrieved from (Esa, 2008)

First, the introduction and problem description are in Chapter 1. In this chapter, it analyses the problem, main system, and the goal of the system. Then in Chapter 2, by using a preliminaries and relevant literature review, the research question is made. Furthermore, this chapter also shows the first model of bladder reservoir which made by Sietse van den Elzen (2018) J.A. Koning (2018), then it is compared by a new design that proposed by drs. W.A. (Wout) Prins as the project manager of Ocean Grazer, which made to minimize the fold. For Chapter 3, it describes the methodology of fold detection analysis which compared various way for fold detection method and the reason for choosing the method. In Chapter 4, the chosen method was validated using first model of Ocean Grazer Bladder Reservoir, then it was compared with experimental study. Chapter 5 explains the answer for the main research question by showing the new model of the bladder reservoir which has fewer fold to have longer lifetime and increase the effectiveness. The report is ended with Chapter 6 for conclusion and future works.

1.1 Problem Description

Today, the Ocean Grazer research group is focusing to make a prototype test in Wadden sea in North Holland. For realizing this, the prototype model must have high enough TRL (Technology Readiness Level) which can indicate that the new technology is ready to be field tested (Mankins, 1995). According to the current design of bladder reservoir which made by

J.A. Koning (2018), it still cannot satisfy M. Van Rooij as the project leader of the Ocean Grazer, because it still has many folds when the prototype is tested which can lead to shorter the life time. It makes the model will not be efficient to be used. For this, a proper analysis must be done for determining the folds, then the new design must can be made to minimize the folds.

1.2 System Description

The system of Ocean Grazer is shown in Figure 1.2. From its figure, it can be seen that Ocean Grazer is a multiple source renewable energy harvester which is located offshore, then the storage system is in the bottom of the system that using bladder reservoir technology. The mechanism of bladder reservoir in energy storage system is described in Figure 1.7. Fluid from the rigid reservoir in number 1, is transport to the bladder reservoir in number 2a. For transport the fluid, the energy is needed because the pressure difference between rigid reservoir and bladder reservoir which comes from hydrostatic pressure of surrounding water. This pressure makes higher pressure on fluid inside the bladder reservoir compared to the fluid inside the rigid body. However, the fluid moves from bladder reservoir to the rigid body through a turbine in number 5, which can generate electrical energy (Prins et al, 2017). The fluid inside the reservoir is separated from the seawater because seawater is corrosive and can destroy the structure inside the reservoir.

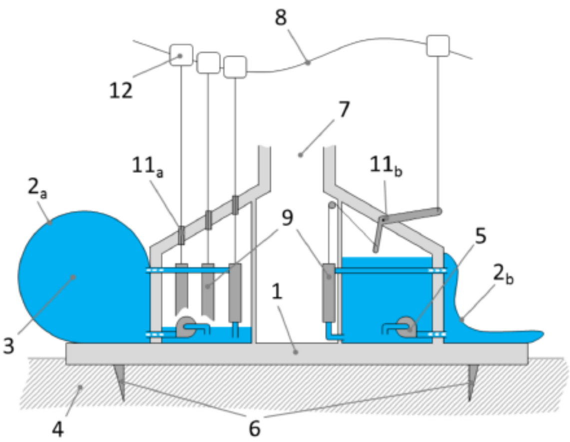

Figure 1. 7: Energy storage system. Retrieved from (Prins et al, 2017)

1.3 Conceptual Model

The conceptual model of this research is shown in Figure 1.8. From its figure, it can be seen that the requirement of the model condition to minimize the fold. For preventing the fold, the design must have no excessive material along the membrane, because it will initiate the fold. To keep the membrane from excessive condition, the availability of space for membrane must be equal or higher than the total area of the membrane itself. Besides that, the stability of membrane during inflation and deflation also must be considered to make all the bladder membrane will increase dan decrease uniformly for preventing the force concentration in one area of membrane because of its weight. To reach that, the membrane must have uniform thickness along the surface.

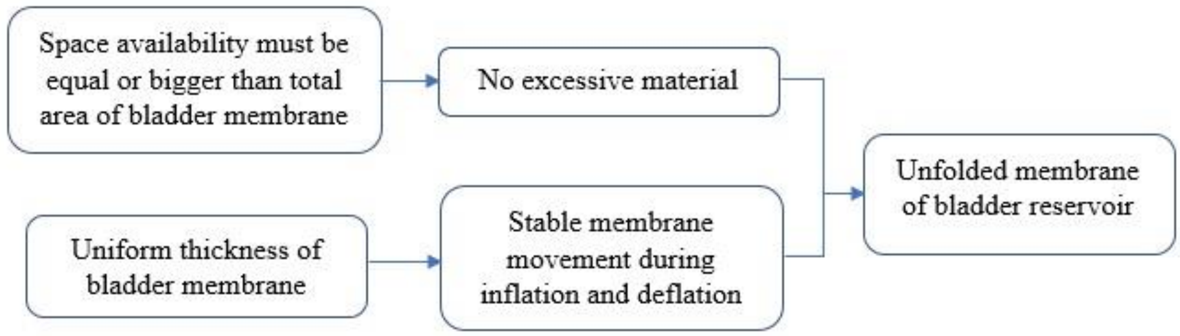

Figure 1. 8: The conceptual model of fold detection analysis on bladder membrane of Ocean Grazer storage system

The conceptual model is very important to define the factor and parameter which is considered for developing the analysis. For the predetermined condition, the hydrostatic pressure will be set as in 50 meters below the sea level condition to simulate the field condition for the planned spot in Wadden Sea. For define the stress concentration effect which caused by fold material, for the rubber membrane, literature study will be done.

In this research, there are included some stakeholders which are a group of people or institution that can impact or be impacted by the outcome of research (Wieringa, 2014). According to that definition, the stakeholder which is included in this research is as follows:

- CTO of Ocean Grazer BV

A research group in University of Groningen initiate to develop the Ocean Grazer project. To keep the sustainability of the project, a private company, Ocean Grazer BV, is created in 2018 for gaining support from the investors and enter the market as a new player. The CTO of the company is the main person who have a full responsibility of the design. He has some requirements for reach the target for the design outcome. On the other hand, he also has to keep the efficiency of production. Therefore, he needs to make sure that a design will have long life time, great performance, but less production cost, before make a prototype test.

- Researchers of Ocean Grazer

Researchers are also the important part for the project because they can give another perspective by brainstorming interdisciplinary knowledge to the design. It can be effective for the company since many possibilities from many perspectives that maybe unconsidered before, will make a bigger chance for solving the problem.

1.4 Problem Definition and Goal Description

According to the Ocean Grazer project which want to analyse the fold forming on the bladder reservoir membrane that will be minimized for longer the lifetime, the problem defined as follows: *there is no analysis to detect the fold structure which can cause the stress* *concentration in bladder membrane that can simulate the effect of the fold to the membrane of bladder reservoir during its lifetime.*

For doing the analysis there are multiple method which can be done to determine the fold forming in rubber membrane of the Ocean Grazer bladder. First, it can be done by making a prototype and do a field test. However, the prototype method will not be efficient since it will take long time and high cost. Second, the analysis also can be done by doing a simulation which will use a computer-based simulation test for the bladder that called constructive simulation (Cohen, 1998). For this research, the using of constructive simulation for analysis will suitable because the simulation keep consider about the surrounding condition of the field and also it will take less cost and time. The goal of this research is to analyze the dynamical system of Ocean Grazer bladder reservoir for minimizing the fold structure during the inflation and deflation process.

Chapter 2

Preliminaries and Literature Review

According to gather relevant studies for doing the research, preliminaries and literature review step was done. In this chapter, it consists of preliminaries that describe the detail of first and new design of bladder reservoir, also the correlation about both of them and the reason of new design is needed to be made.

2.1 Preliminaries

In preparation step of this research, the first and new design was compared. The comparison purpose was to know about the detail about both of the design and the reason to develop the new design.

2.1.1 First Bladder Reservoir Design

<u>Design Detail</u>

In the first design of bladder reservoir, it used donut shape for the bladder design where the rigid body was in the center of bladder reservoir. The design was adopted from Ultra High Performance Vessel (UHPV) which was designed by Thin Red Line Aerospace, as shown on Figure 2.1 (Elzen, 2018). The design purpose of UHPV by using a pumpkin shape was for holding high stress from fluid pressure inside the balloon. The research for this balloon design for withstands the force was considered since 1919 (Taylor, 1963). Then based on that result, NASA make a development of design by creating Ultra Long Duration Balloon (ULDB) which adapt a pumpkin balloon design (Smith, 2004).

Figure 2. 1: Ultra High Performance Vessel (Thin Red Line Aerospace). Retrieved from M. Pagitz et al. (2007).

According to the previous research, Ocean Grazer Bladder reservoir has the similar behaviour with the UHPV. Therefore, the first design of ocean grazer was adopted from pumpkin design, but since Ocean Grazer must have a rigid body, the design was modified by add the rigid body in the center. Then the bladder membrane shape was designed as shown on Figure 2.1 and Figure 2.2 for the cross-sectional image shape.

Figure 2. 2: First membrane design of bladder reservoir. Retrieved from J.A. Koning (2018).

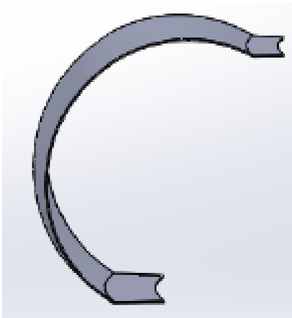

Figure 2. 3: Cross-sectional shape of bladder membrane. Retrieved from J.A. Koning (2018).

According to the energy production output which needed as minimum requirement, the dimension of bladder reservoir was calculated and scaled to make the prototype for the lab test. Then, based on the available space of test set-up, the width of the frame was set for 60cm. Furthermore, the rest of dimension can be seen in cross-section image on Figure 2.4

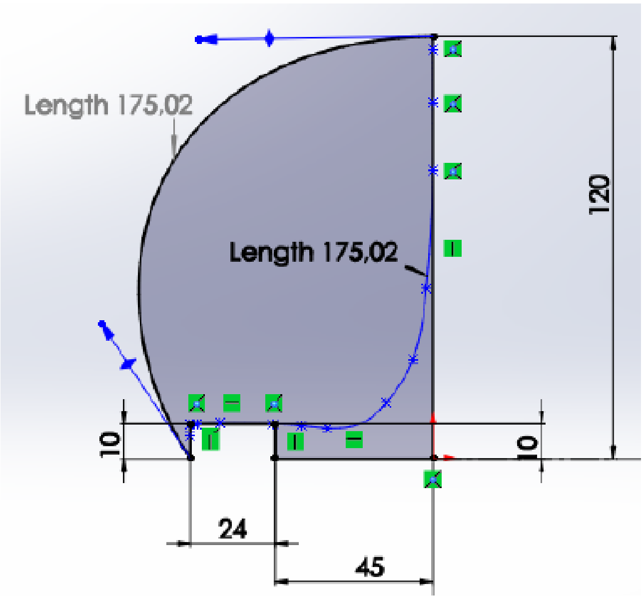

Figure 2. 4: First bladder design dimension. Retrieved from J.A. Koning (2018).

Membrane Material

To keep the performance of bladder reservoir for Ocean Grazer, the material of bladder membrane has some requirements. Besides it can operate under the pressure without being failure, the material also has to be work without get significant influence from the surrounding condition. Furthermore, it also must prevent the sea water to go inside the bladder.

According to the relative properties of various rubber which can be seen on Table A.1, the suitable material for bladder membrane is Ethylene propylene diene monomer (EPDM) which has good performance in water and abrasive resistant because its mechanical and chemical properties (Khalaf, 2017). The material must have good performance in water and abrasive resistant because the bladder location which on the bottom of the sea. Besides that, since the temperature in bottom of the sea is low, this will be the advantage of using EPDM because the operating temperature of EPDM is -50 and 150 Celsius (All Seals, 2019). Furthermore, EPDM is also the common material which is usually used in gasket production that have same behaviour with bladder membrane because it prevents fluid from going through it. In addition, since it is used as the material for gasket which is mass produced, the price is cheap and have sustainable availability.

Design Evaluation

According to the evaluation of first model of Ocean Grazer Bladder Reservoir which made by J.A. Koning (2018), the design made the membrane tends to fold as the design analysis by C.B. van den Hoek (2019) which can be seen on Figure 2.5. Besides that, based on experimental result from Ocean Grazer itself, there was a different result of bladder shape in deflated condition when it was compared with the simulation result.

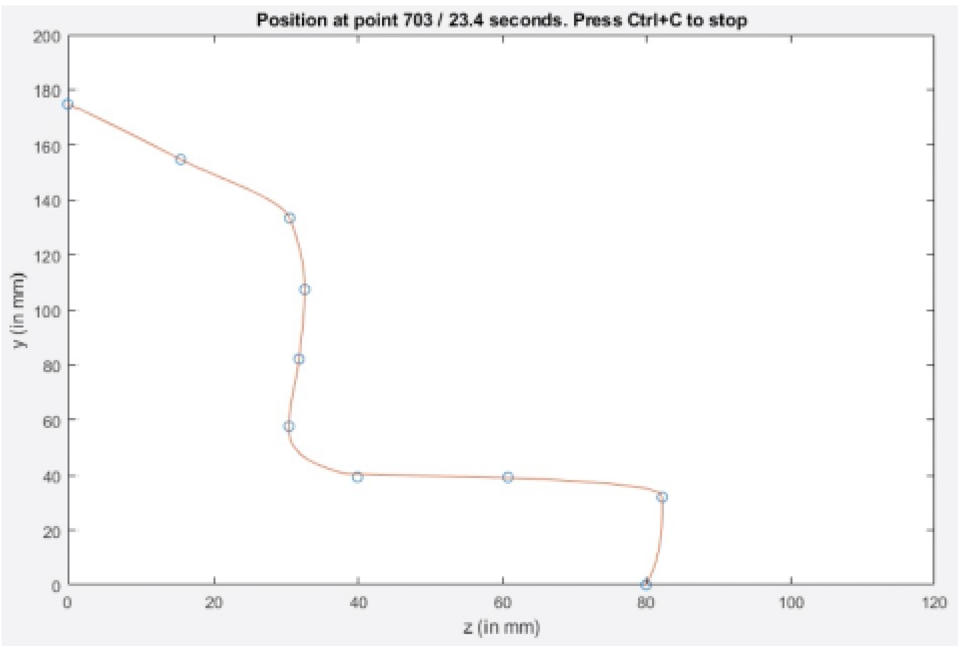

Figure 2. 5: Bladder profile in a half way between full deflates and fully inflates. Retrieved from (Hoek, 2019)

As shown on Figure 2.4 which the result from J.A. Koning (2018) research, based on the simulation, it defined that there was no fold along the bladder membrane during the operation process because the total length of bladder membrane in cross-sectional between in fully inflated and fully deflated condition was equal. On the other hand, on Figure 2.6 which was the experimental result from Ocean Grazer, it shows that there was a fold that formed in the bladder membrane when it was in fully deflated condition. Therefore, drs. W.A. (Wout) Prins proposed a new idea to develop the design of which can minimize the fold.

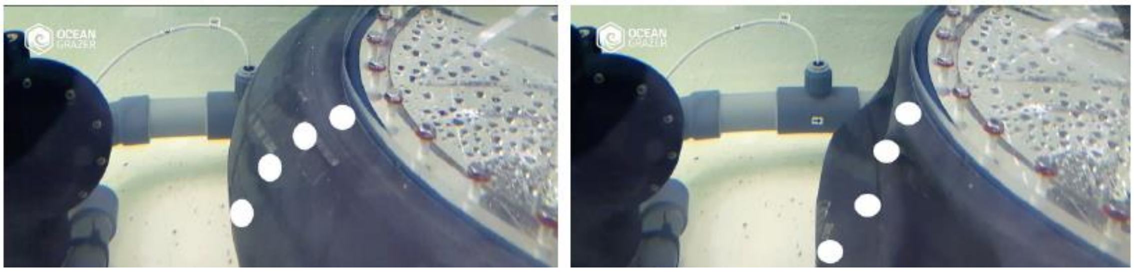

Figure 2. 6: Left: Fully inflated bladder, right: Fully deflated bladder when the folds was formed. Retrieved from (Ocean Grazer, 2015)

2.1.2 New Bladder Reservoir

<u>Design Detail</u>

The new design which developed by drs. W.A. (Wout) Prins is adopting inflatable dam design. Instead of using a donut shape like the J.A. Koning (2018) design, he prefers the use of the square design as shown on Figure 2.7 which has fewer folds in transverse direction. However, since there is no sidewall in bladder reservoir because it will be placed in the middle of the ocean, the design will be shaped like a square. Then, the total dimension of the bladder reservoir is almost the same of the previous design as shown on Figure 2.8, because it is required to fulfil the minimum power production target for increase the TRL which indicates that actual component will be reliable to use. The new design of bladder reservoir is designed using Solidworks.

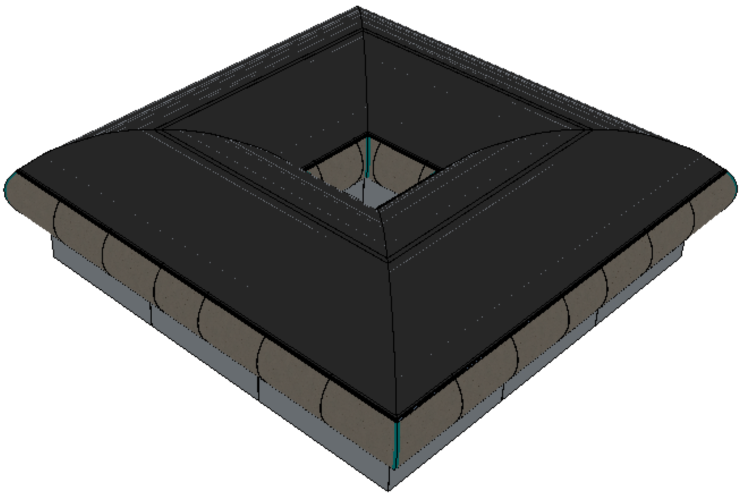

Figure 2. 7: Bladder reservoir design by W.A. Prins. Retrieved from (Ocean Grazer, 2019)

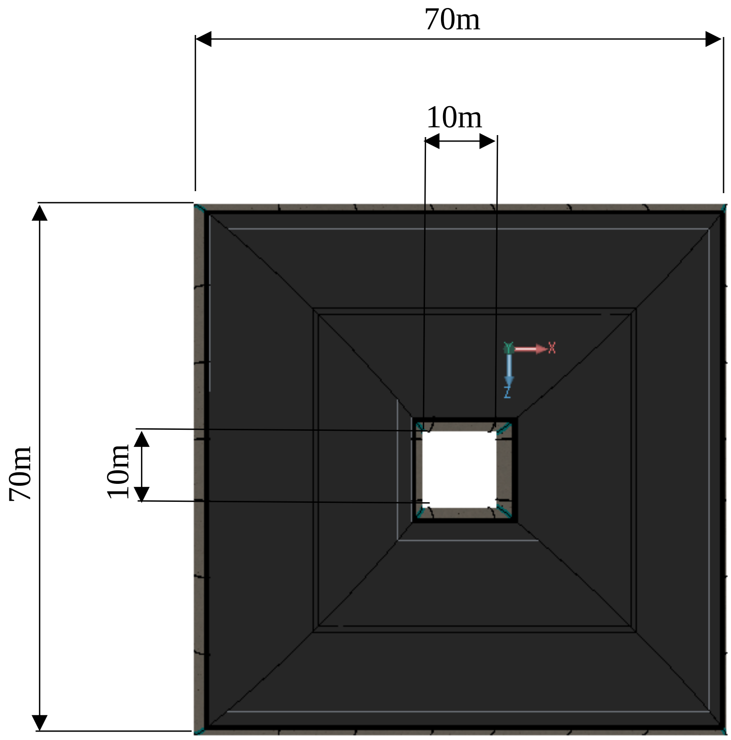

Figure 2. 8: Dimension of bladder reservoir. Retrieved from (Ocean Grazer, 2019)

Besides that, another important thing which must be considered is the total length of the bladder reservoir membrane to make sure there will be no excessive material. Therefore, to minimize the fold because of the excess, the dimension of bladder reservoir in inflates and deflates condition must be equal. Furthermore, the movement of the bladder itself must be controlled, especially on fully deflated condition. For controlling the movement, a rigid body is designed to help the bladder to be set in flat condition as can be seen on Figure 2.9.

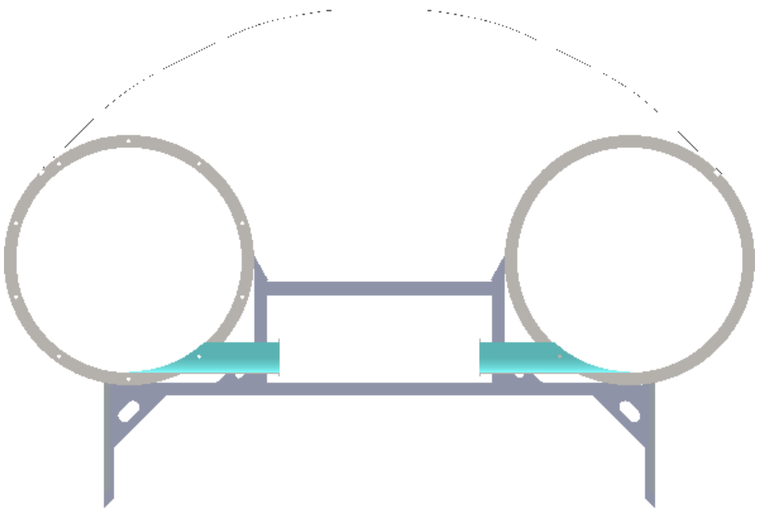

Figure 2. 9: Cross-sectional image of new bladder reservoir design. Retrieved from (Ocean Grazer, 2019)

Membrane Material

Based on the evaluation of first model bladder reservoir design, there was no significant problem with the material. Therefore, for the new bladder design, EPDM is still be used as the material of membrane due to the effectiveness of performance and cost efficiency.

2.2 Literature Review

The literature review contains about the literature which can support the research. The literature will be consisted of some information. First, the literature about fatigue limit and factors that can influence it. Second, the stress concentration effect on the fatigue limit of the material which will influence the lifetime. Then, the application of inflatable dam that has similar behaviour of the using rubber membrane.

2.2.1 Fatigue Limit

For increasing the TRL, the Ocean Grazer Bladder Reservoir must have a long lifetime. The one important factor to keep long lifetime performance is fatigue limit. Fatigue limit is maximum stress in a number of cyclic loading which can be applied to the material without failure (Deutschman, 1975). Fatigue failure is one important thing that must be prevented because it is really damaging and no warning before although the stress which be applied on the material is much lower than the ultimate stress.

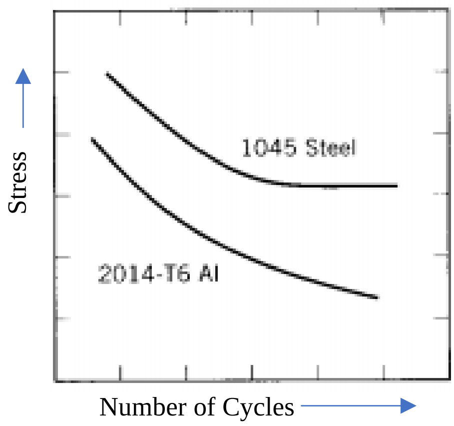

Figure 2. 10: Stress and Number of cycles (S-N) diagram. Retrieved from (Roylance, 2001)

From Figure 2.10, it shows that more loading cycles makes the stress value for the material will decrease. However, at some point, the values will be constant although the number of cycles increase. Based on Figure 2.10, the lifetime of material can be predicted, so the predictive maintenance of the component can be scheduled. Besides that, the designer also can use the diagram for calculate the cost effectiveness of the component production because they can set how long and how tough their design based on the requirement and design purpose.

Factor that influence the fatigue limit

During the operation of the component, there are many kinds of different condition of a test. These conditions are important factors which must be considered because it will give effect to the material. There are some factors which can influence fatigue. J. Marin (1962) make a list of factors which must be considered for designing a component as can be seen on Table 2.1, to get optimal fatigue limit according to the design purpose. However, these factors can not be used instantly because every factor which is based on specific specimen and test.

Table 2. 1: Factors Influencing Fatigue Strength. Retrieved from (J. Marin, 1962)

Factors Influencing Fatigue Strength	
Material Effects 1. Chemical composition 2. Failure condition 3. Material variation 4. Size and shape 5. Speed 6. Understressing & overstressing	**Environmental Effects** 1. Corrosion 2. Rest periods 3. Superimposed static stress 4. Temperature 5. Varying amplitudes 6. Exposure to nuclear radiation
Manufacturing Effects 1. Fretting fatigue and fretting corrosion 2. Heat treatment 3. Method of manufacture 4. Stress concentration 5. Surface treatments	**Miscellaneous Effects** 1. Surface fatigue 2. Combined stresses

Furthermore, another approach from Carl F. Zorowski (2002) states the modifying factors of the factor limit according to the equation are as follow (Zorowski, 2002):

$$\sigma'_e = k_a k_b k_c k_d k_e \sigma_e$$

where σ'_e= fatigue limit of part

σ_e = fatigue limit of test specimen

k_a = surface factor

k_b = size factor

k_c = load factor

k_d = temperature factor

k_e = miscellaneous effect factor

The miscellaneous effect factor is a group of effect which is included by residual stress, corrosion, electrolytic plating, metal spraying, loading or rate changing of frequency, fretting corrosion, and stress concentrations (Zorowski, 2002). Some miscellaneous effects can increase, but some also can decrease the fatigue strength. Compressive residual stress such as surface hammering and cold working on surfaces can increase the fatigue strength. However, corrosion will give a negative effect because it makes rougher surface which easier for crack to be propagated then results lower fatigue strength. Electrolytic plating also will reduce the fatigue strength until 50% and metal spraying will give 15% lower fatigue strength. The changing of rate and loading frequency will not give a significant effect, but they can increase the temperature and initiate the corrosion. Fretting corrosion effect especially at tight joint is hard to quantify due to its movement in microscopic scale. Then stress concentrations which can cause by the shape or a part of geometry will also reduce the fatigue strength (Zorowski, 2002).

2.2.2 Stress Concentration Effect

As can be seen on Table 3.1 and the approach from Zorowski (2002), stress concentration is one of the factors that can influence the fatigue limit. On the other hand, the reason of minimizing the fold in the bladder reservoir membrane of Ocean Grazer is to prevent the stress concentration effect that will gives effect to fatigue limit of the material which also considered for designing a material (Arola, 2002). Stress concentration will happen in the fold structure because of the bending stress as shown on Figure 2.11 that can increase the probability of fatigue failure (Gurt, 2015). Furthermore, fatigue failure is one of the most common factors that leads the material failure (Wang, 2016).

Figure 2. 11: Bending characteristics of rubber membranes. Retrieved from (Gurt, 2015)

Basically, stress concentration can be neglected for low cycle that under 1000 cycles or static loads and the material is not brittle (Zorowski, 2002). However, since bladder membrane is designed for long term operation, this effect must be considered, unless the membrane will fail and the bladder reservoir will not work anymore (DIN, 2007).

The common way to test the effect of stress concentration in fatigue limit is by using notch in the material which will get stress. The notch is used for make a stress concentration along the profile. Smaller notch will give more stress concentration. Then, more stress concentration will make a material to have lower fatigue limit as can be seen on Figure 2.12.

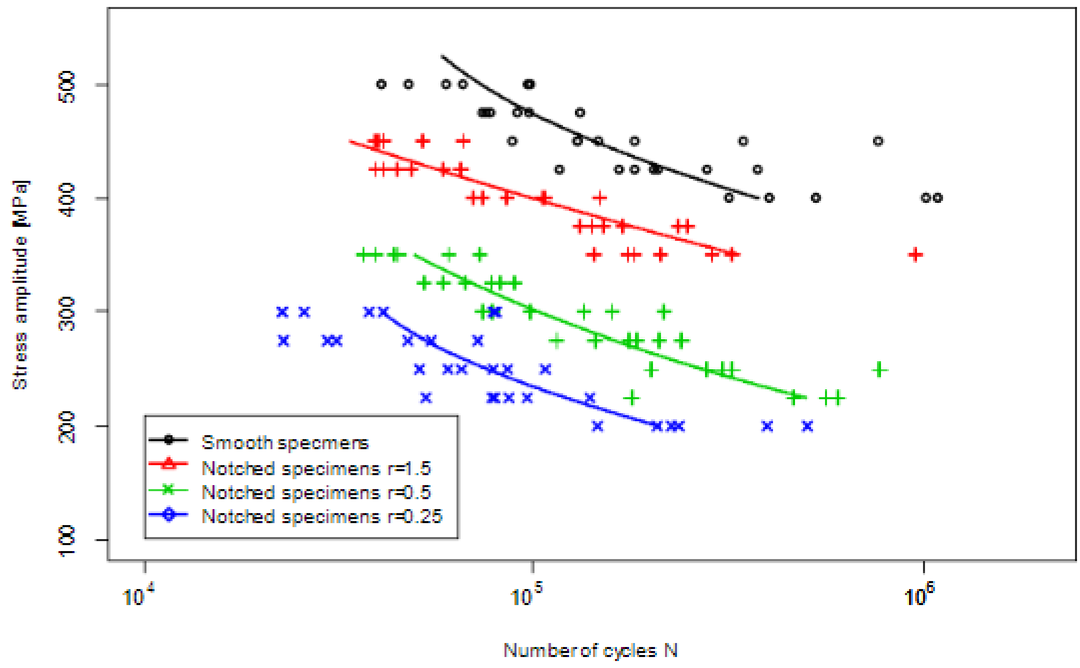

Figure 2. 12: S–N curves result with some various notched specimens. Retrieved from Strzelecki (2019)

2.2.3 Inflatable Dam

Other application of rubber membrane use for similar behaviour with bladder reservoir is inflatable dam. According to the design and analysis of reinforced rubber membranes for inflatable dam by R. Gurt (2015), the dam design has fewer fold structure. As can be seen on Figure 2.13, he uses a straight design for the inflatable, then when it deflates, the rubber membrane is laid on the bottom of the weir (Gurt, 2015).

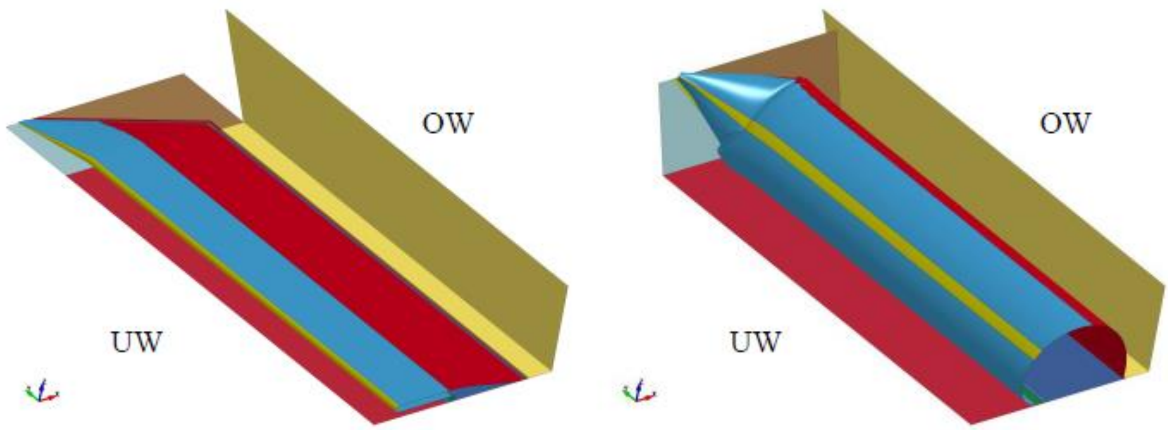

Figure 2. 13: Left: deflated dam, right: water inflated dam with headwater. Retrieved from (Gurt, 2015)

In this design, folds take place when the dam is fully inflated. This is happened because the excessive material which happened in an area near the side wall and it can be a disadvantage as shown on Figure 2.14. On the other hand, this excessive material can not be removed because it is needed when the dam in fully deflated condition so it can completely be laid at the bottom of the weir unless the dam membrane will be damaged during the flood (Gurt, 2015).

During the operation, folds can give a bad effect for the inflatable dam membrane. Folds can make the water go through them, which makes the dam does not work optimally. Besides that, the stress concentration also will decrease the lifetime of the bladder membrane. However, although there is a stress concentration which makes by the fold near the side wall, there is no fold detectible in the top of inflatable dam membrane surface in the transverse direction (Gurt, 2015).

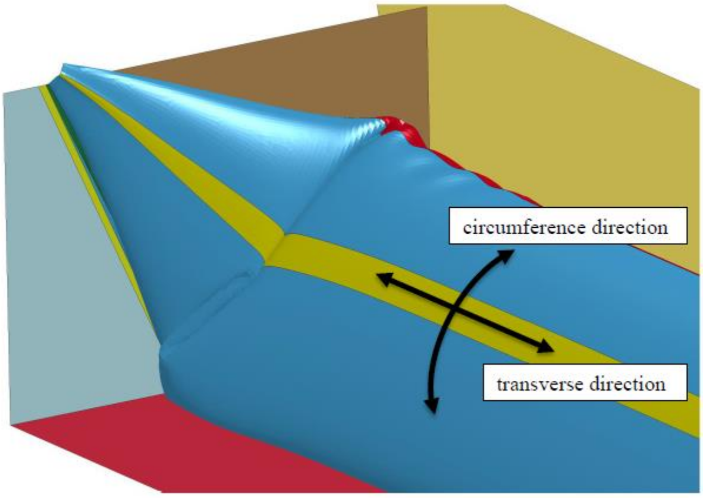

Figure 2. 14: Folds near the sidewall. Retrieved from (Gurt, 2105)

2.3 Research Question

Based on the problem statement and research goal, the research question can be determined as follows:

"How does the bladder membrane of new conceptual bladder reservoir design, of Ocean Grazer, behave under the hydrostatic pressure to prevent the fold structure during its operation?"

From the research question, the research sub-question can be determined to answer the problem, which are:

1. What factor that makes the bladder design have a fold structure?
2. How should the bladder be analyzed to detect the fold structure?
3. How can the new bladder design be proven?

2.4 Approach

As described in the literature review, the approach for this research will use a 3D analysis with computer-based simulation test which mainly detect the stress concentration which cause by the fold during its operation time. The test will use the new model that proposed by drs. W.A.

(Wout) Prins to prove if it has fewer fold. To perform the simulation, the test will be done in Ansys.

This research is separated into two parts for answering the research sub-question. To answer the first and second research sub-question, the new model will be compared with the old model. Then to answer the third research sub-question, the dynamical analysis will be done by doing a fully inflate and fully deflates simulation to get stress distribution analysis result. In the rest of this thesis, we will assume that the analysis is performed for a reservoir storage system that is operational at 50m under water.

Chapter 3

Fold Structure Detection Methodology

Fold detection analysis along the membrane of bladder reservoir during its operation, can be done in many ways. In this chapter, it will describe the various method of fold detection analysis, the compatibility of method with the bladder reservoir, the requirement parameter for the bladder test, and the research limitation for fold detection in membrane of bladder reservoir.

3.1 Fold Structure Detection Method

As described on the preliminaries and literature review, the fold structure detection used stress distribution analysis in bladder membrane. The stress distribution analysis itself used Finite Element Method (FEM) for the basic method to see the behaviour of material during the condition that was given.

3.1.1 2D Finite Element Analysis

Finite Element Analysis (FEA) is a common method to analyze the behaviour of material when it was given a specific surrounding condition (Jagota, 2013). One of the methods that is usual to be used is two-dimensional analysis because it simplifies the calculation which the condition along the material can be represented in 2D plane as shown on Figure 3.1.

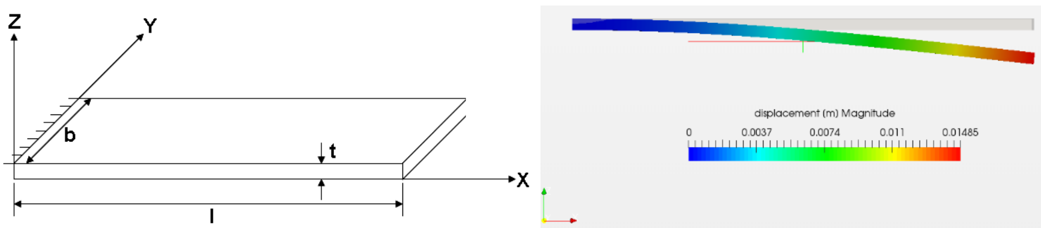

Figure 3. 1: Two-Dimensional Analysis of Cantilever Beam, Retrieved from (DIANA, 2012)

However, the 2D Analysis was only can be done if the external force was distributed uniformly in thickness (Y) direction did not give any effect on the material in Y-direction, because this analysis neglects the thickness. Furthermore, the disadvantages of 2D analysis result was overestimate the stress and deflection (Yao, 1998).

According to condition of Ocean Grazer Bladder, the 2D analysis was not suitable to be used for fold detection in Bladder. It was because the shape of bladder membrane which in donut shape, made the pressure along the bladder was not distribute in the same direction along the Y-direction.

3.1.2 3D Finite Element Analysis

In 3D Finite Element Analysis, it is more complicated than 2D analysis, but the result is more similar to the experimental result (Yao, 1998). It was because the force from the inside and the surrounding condition was calculated in 3D. Besides that, the advantage of three-dimensional analysis was also suitable for analyze a complex shape which the thickness can not be neglected because it maximizes stress and displacement approach along the shape as the example shows on Figure 3.2 which used 3D analysis for stress distribution along the vessel (Geramy, 2003).

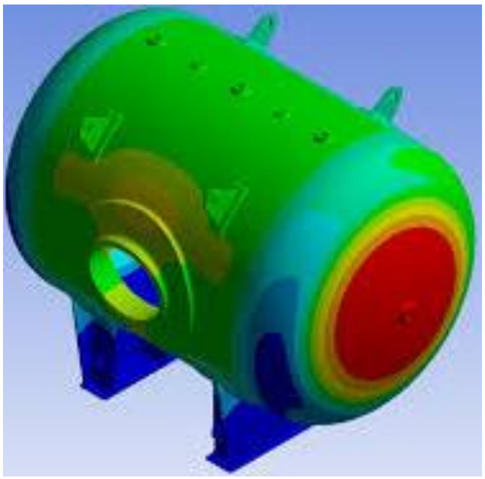

Figure 3. 2: 3D Finite Element Analysis in a vessel. Retrieved from (Tamboli, 2014).

According to the bladder reservoir shape, this 3D FEA was more suitable for fold detection since the analysis will be based on stress distribution and displacement along the shape of bladder membrane.

3.2 Load

The bladder reservoir will be tested in the simulated condition in prospective area. The assumption factor which will be simulated as the persistent situation are bladder reservoir own weight and hydrostatic pressure which will be calculated based on the condition 50 meters below the sea level.

To calculate the hydrostatic pressure on 50 meters below the sea level, it can be defined by using this equation:

$$P_{-50} = P_{atm} + \rho g h$$

where P_{-50} = Hydrostatic pressure at 50 meters below the sea level (N/m^2)

P_{atm} = Pressure at the sea level (1.01325 x 105 N/m^2)

ρ = Density (Kg/m^3)

g = Acceleration due to gravity (9.81 m/s^2)

h = Height distance from the sea level (m)

Therefore,

$$P_{-50} = 604087.5\ {}^{N}/_{m^2} \approx 604\ {}^{kN}/_{m^2}$$

On the other hand, the water inside the bladder have different pressure since it is in a closed space and separated from sea water. The pressure of water inside the bladder can be calculated by using this equation:

$$P_{in} = \rho g h$$

which the result is,

$$P_{in} = 489028.5 \, {}^{N}/_{m^2} \approx 489 \, {}^{kN}/_{m^2}$$

3.3 Research Limitation

To increase the TRL level of bladder reservoir for Ocean Grazer, the material of bladder membrane has some requirements. Besides it can operate under the pressure which has been defined before, without being failure, the material also has to be work without get significant influenced from the surrounding condition. Furthermore, it also must prevent the sea water to go inside the bladder.

According to the relative properties of various rubber which can be seen on table A.1, the material will get other effect from its surrounding such as temperature changing of seawater, and land shifting. Therefore, to minimize the parameter for the effectivity and the efficiency of this research, some conditions which can give effect for the material performance during the operation time, were put as the limitation of the research.

Chapter 4

Fold Structure Detection Method Validation

In this chapter, the 3D Finite Element Analysis is validated by using the result comparison of 2D simulation and prototype test, then the 3D simulation is done to make a validation of method using ANSYS.

4.1 First Bladder Design Fold Detection Analysis

According to J.A. Koning (2018) research, the bladder membrane of first model does not have fold because the total length of membrane between fully deflated and fully inflated condition was equal in cross sectional section as shown on Figure 4.1.

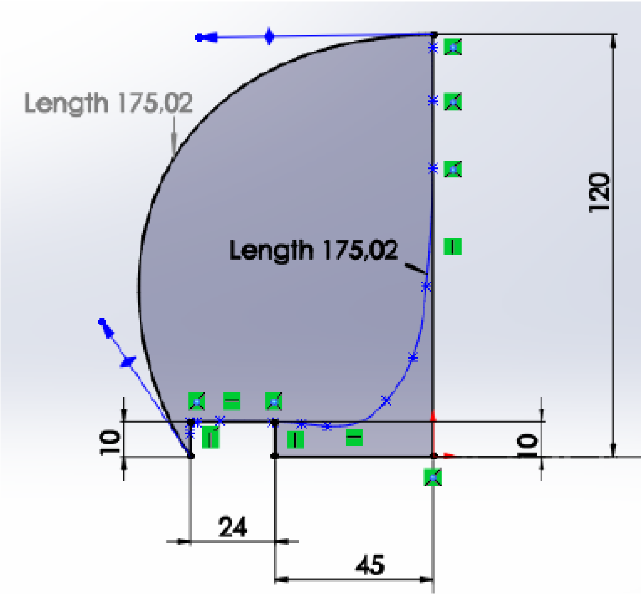

Figure 4. 1: The cross-sectional image of first bladder reservoir model for Ocean Battery system. Retrieved from J.A. Koning (2018).

However, based on the result of 3D analysis as shown on Figure 4.2, it can be seen that the folds were formed in circular way. It was happened because the total space area for the bladder membrane in that condition was smaller than the total area of the bladder membrane itself. As can be seen on Figure 4.3, based on Solidworks calculation, the total of inflated bladder area which green colored was 314.4 m^2. On the other hand, the total available space for the bladder in rigid body which red colored in Figure 4.3 was 287 m^2. Therefore, the excessive material can not be placed in smooth contour when in fully deflates condition, then it made fold structure along the bladder membrane.

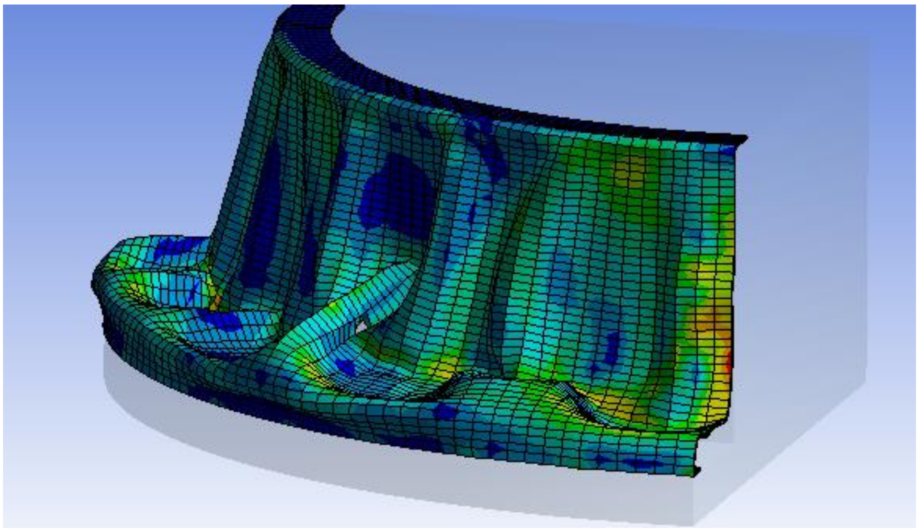

Figure 4. 2: The fold structure of bladder membrane in fully deflated condition from 3D FEA result.

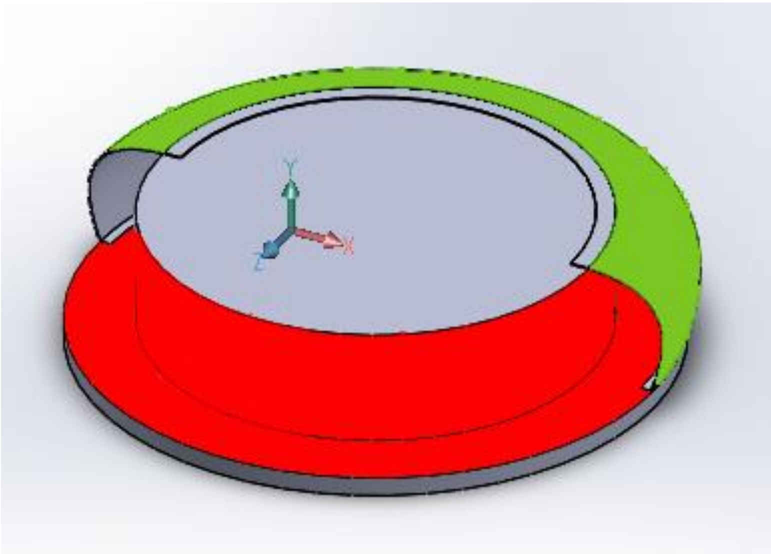

Figure 4. 3: Difference on the total bladder area and available area on rigid body

4.2 Comparison with Experimental Study

To validate the simulation analysis, the fold based on FEM prediction result was compared with the experimental result from Ocean Grazer (Palaniappan, 1997). Therefore, the 3D FEA result was compared to the experimental result for the validation if this method was suitable to be done for detecting the folds along the bladder membrane of Ocean Grazer.

Based on the bladder reservoir prototype test on Figure 2.6 in design evaluation chapter, there was a difference between the simulation result and actual test result. According to those result, the folds are formed in similar structure. However, there is still a difference which is in real prototype test, the folds structure was not formed in the same structure every inflation and deflation cycle. The difference come from pressure distribution assumption, since in simulation, pressure distribution inside and outside the bladder is assume as uniform distribution. On the other hand, in actual condition, pressure distribution depend on the water flow which was not uniform because of the outflow of water from bladder to rigid body used a pipe in a location that lead a turbulent fluid flow inside the bladder. Nevertheless, instead of the fold shape difference, the 3D FEA can be validated for the fold detection as its result was in line with the experimental result in general.

Chapter 5

Fold Structure Detection Analysis in New Bladder Reservoir Design

In this chapter, the new design which proposed by drs. W.A. Prins will be tested by computer-based simulation using ANSYS. This simulation will define the reliability of design to prove that it can be applied and work effectively, but still efficient.

5.1 Volume Measurement

Before doing a dynamical analysis for detect the fold, the volume inside the rigid body and bladder must be measured because volume inside the bladder must be equal or more than inside rigid body volume to make the bladder works optimally. According to the volume measurement using Solidworks, the total volume of space for water inside rigid reservoir and the bladder in fully inflated condition is as follows:

- Water volume inside rigid body = 20869.45 m^3
- Water volume inside bladder = 24538.03 m^3

Therefore, when the bladder is in fully deflated condition and all of the rigid body is already in full condition, it still have 3668.58 m^3 water inside the bladder. Based on this result, it indicates that the bladder reservoir design is reliable and can be applied effectively.

5.2 Membrane Thickness Analysis

After measuring volume of the new design for make sure that the design will work efficiently, the minimum membrane thickness of the bladder reservoir also must be analyzed due to the force from hydrostatic pressure and water pumping when the rubber is inflated. This analysis is important to prevent the rubber membrane of bladder reservoir from permanent deformation and failure, unless the membrane must be thicker.

In this research, the new design of bladder reservoir membrane use 15mm thickness of rubber sheet. To determine the maximum pressure that can be applied on membrane surface, the stress analysis will be done in fully inflated and fully deflated condition. The pressure will be determined using equation as follows:

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

where P = Pressure (N/m^2)

A = Area (m^2)

F = Force (N)

The calculation in this research is made with static finite element analysis software ANSYS. Then, the pressure for the fluid is replaced by load vector along the surface which will result an equivalent pressure as the hydrostatic pressure (Haßler, 2008) (Maurer, 2010). Because of the symmetry, only a quarter of bladder reservoir has to be modelled.

5.2.1 Inflated Condition

During the inflation process of the bladder reservoir, inflation pressure must be greater than hydrostatic pressure. However, due to the volume comparison between inner bladder and inner rigid body, the bladder membrane will reach its maximum pressure without get excessive stress because all the water inside rigid body have been transported to bladder as be seen on Figure 5.1. Therefore, in this condition, the membrane will be in safe condition.

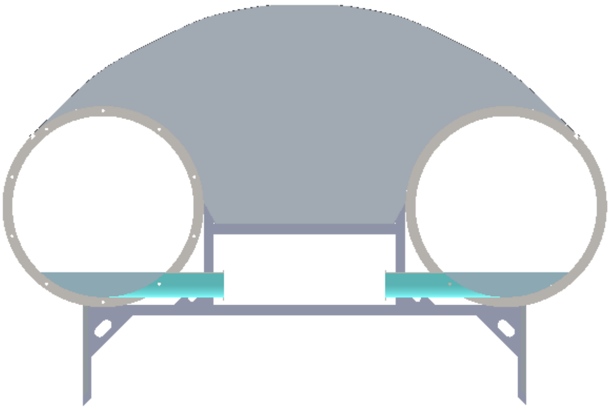

Figure 5. 1: Bladder reservoir in fully inflated condition

5.2.2 Deflated Condition

In the fully deflated condition, as described on volume measurement in Chapter 5.1, there are still water inside the rigid body because volume inside the bladder is bigger than inside rigid body, so when the rubber deflates and water transports from bladder to rigid reservoir, not all water can be transported to rigid body due to its volume. The water which left inside the bladder will help the membrane to not get excessive stress which can break it by using the pressure of inner water as shown below on Figure 5.2.

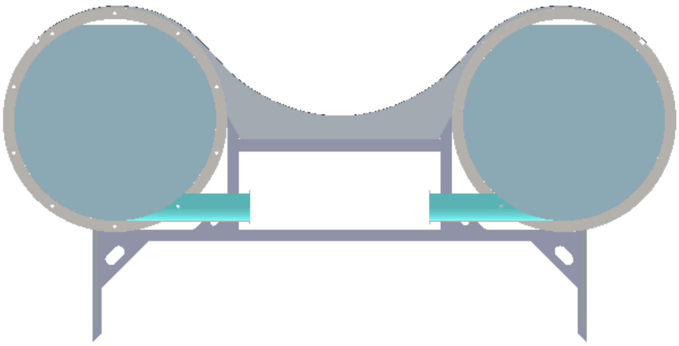

Figure 5. 2: Bladder reservoir in fully deflated condition

After determine the safety pressure limit to use 15mm rubber sheet as the bladder reservoir membrane of Ocean Grazer, the next step is to detect fold structure in membrane of bladder reservoir during its operation. As described on the literature review, the fold can cause stress concentration effect on the bladder membrane which will increase the probability of fatigue failure. However, it has to be prevented because increasing fatigue failure probability will give a shorter lifetime. Therefore, a dynamical analysis of bladder reservoir during the operation, especially the movement of rubber membrane, is important to be done for determining the folds which formed on the membrane.

In this research, the fold detection analysis using 3D Finite Element Analysis was done to the new model of bladder design to compare with the fold structure in the previous bladder membrane, during inflation and deflation process. The analysis uses 3D method to consider the three-dimensional failure.

5.3 New Bladder Design Fold Analysis

For the new design of bladder, based on result evaluation for first design, the analysis also done with 3D analysis. The result of fold detection analysis during bladder reservoir operation time was the bladder have no fold along the surface in fully inflated condition, because according to the volume comparison between total volume of bladder and rigid body, it was on the maximum volume which all of membrane was stretched out and put it on the normal condition as can be seen on Figure 5.3. Furthermore, this condition also applied when the bladder reservoir is in fully deflated condition. The contour of rigid body helps the membrane to form without has folds as shown on Figure 5.2. Besides that, the space between outer and inner rigid body also helps the membrane to place the extensive material and make the length of membrane equal for inflated and deflated condition as shown on Figure 5.4.

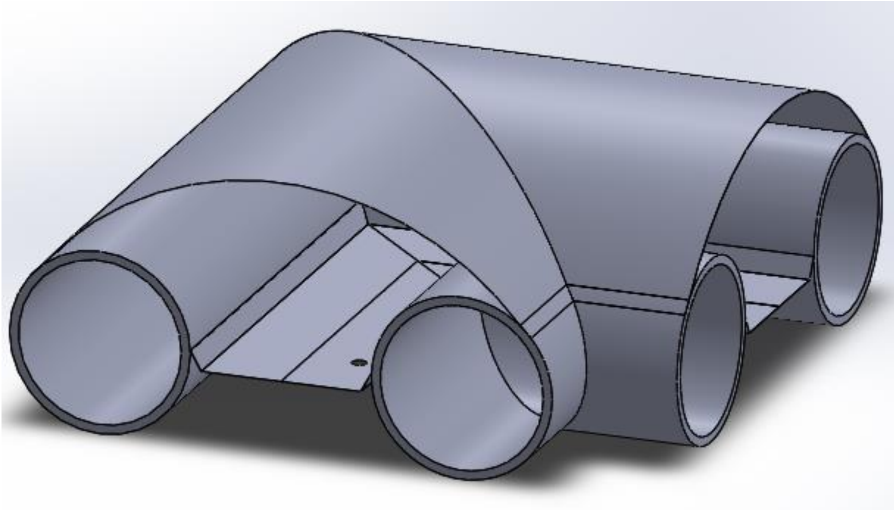

Figure 5. 3: Bladder reservoir in fully inflated condition

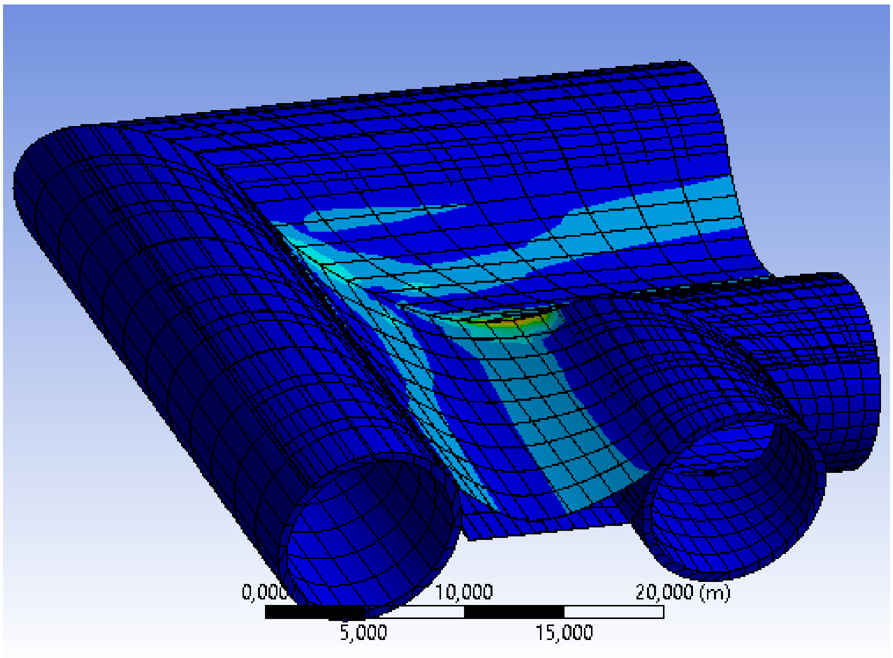

Figure 5. 4: Bladder reservoir in fully deflated condition

However, in the middle of inflation and deflation process, there is a fold in along the membrane of the bladder as shown on Figure 5.5. The fold structure can not be prevented because in this condition, the membrane is pushed to smaller dimension as can be seen on Figure 5.6 which based on the Solidworks calculation of the new bladder design, the total length of bladder membrane in fully inflated condition was 31.34 meters on cross-sectional area, but the available space for the bladder between two tubes of rigid body was only 20 meters.

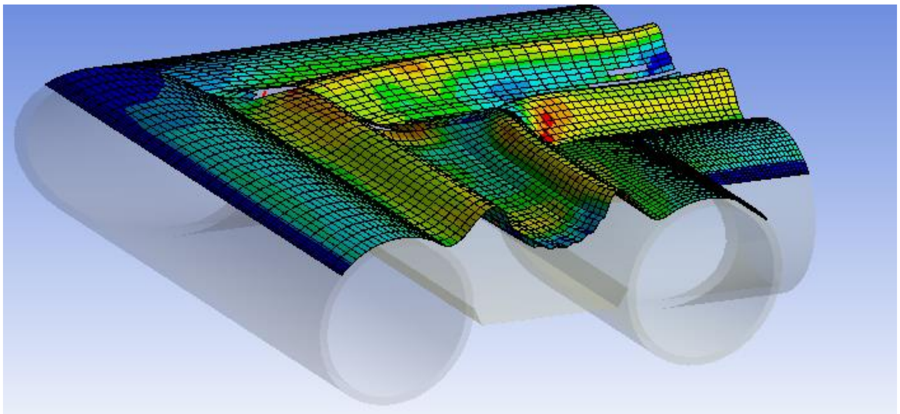

Figure 5. 5: Fold structure on bladder membrane in the middle of inflation-deflation process.

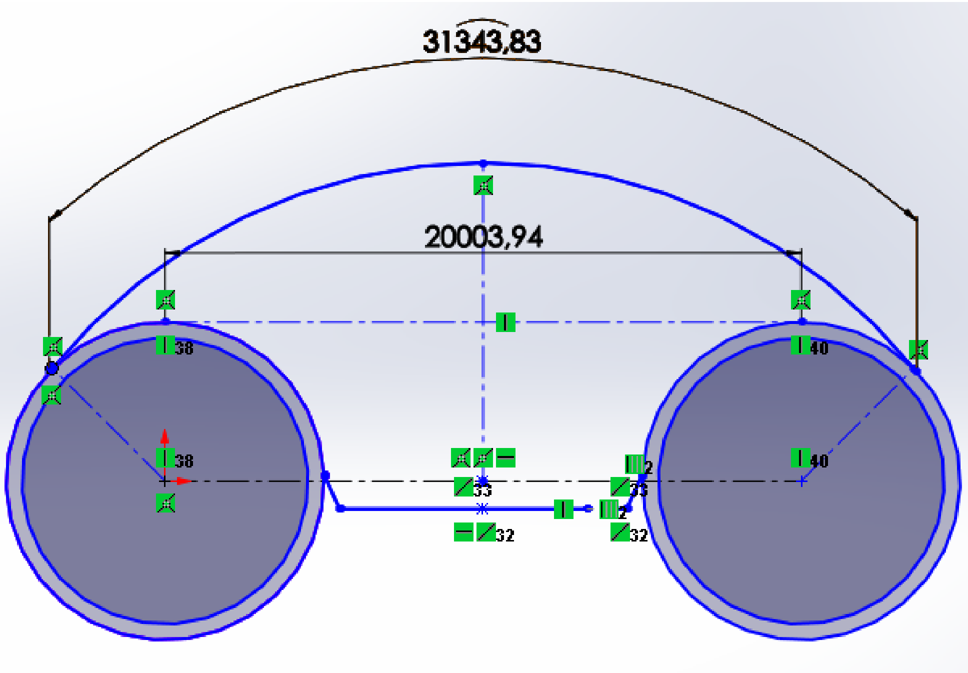

Figure 5. 6: Comparison of Membrane Length and Available Space in Rigid Body (in milimeters)

Nevertheless, based on the several tests and calculation that have been done, the new design of bladder reservoir is still be proven to minimize the folds which formed on the membrane when it was compared with the first design, because the fold radius in the new model is bigger than first model and bigger radius will results lower stress concentration as can be seen on Figure 5.7 and 5.8. Therefore, the lifetime of membrane can be longer for its operation.

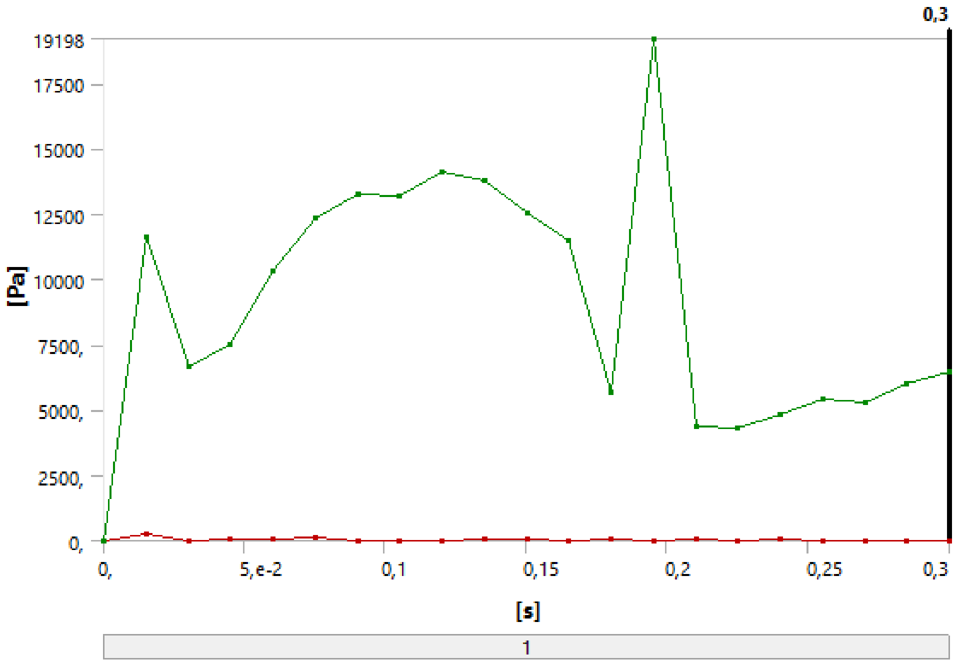

Figure 5. 7: Stress value plot along the membrane on first bladder design during deflation process

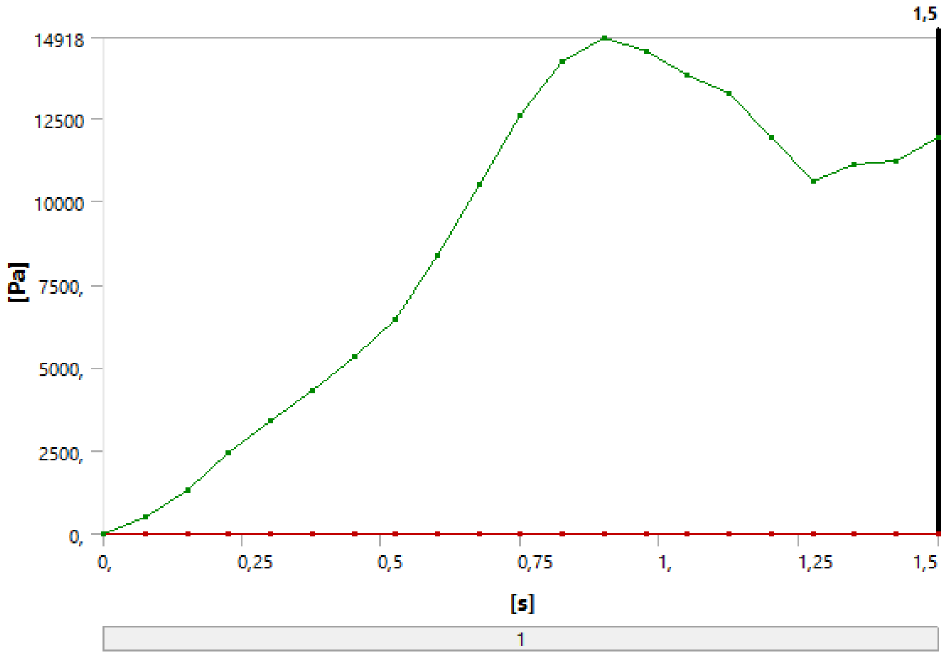

Figure 5. 8: Stress value plot along the membrane on new bladder design during inflation process

Chapter 6

Conclusion and Future Works

The analysis of the new bladder design of Ocean Battery system is done numerically based on three-dimensional finite element method analysis using ANSYS which use the model from Solid Works. Since the problem of previous design was the fold on circular shape when the bladder deflated, the new design adopted the structure of inflatable dam that had no fold structure along the straight part. Furthermore, to take the simulation, the new design which had been proposed, was tested using ANSYS simulation. The main important parameters were set based on the requirement from Ocean Grazer that want to take the prototype test in Wadden sea with 50 meters in depth. For validating the new design to be performed in the prospective surrounding situation, several tests were performed to simulate the stress and fold detection analysis during its prospective operation. Then the results were compared to the first design for making sure that the new design was better than the previous one. The first test was validating the membrane could bear the stress which given by hydrostatic pressure from seawater and inner water pressure from water inside the bladder. In this test, EPDM was used as the material of bladder membrane due to its properties and similarities of behaviour in other application. Furthermore, according to the test, there was no stress concentration on membrane of bladder reservoir. It was because the comparison between volume in bladder reservoir and rigid body which the total volume inside the bladder were bigger than the total volume of inside the rigid body. Therefore, there will be no excessive stress during inflation and deflation. After that second test was the fold detection analysis. According to the 3D fold detection test after validating the method using the first model, folds only happened in the middle of inflation and deflation process. In maximum condition, either the bladder was in fully inflated or fully deflated condition, there was no folds formed. It was happened because the shape of rigid body which helped bladder membrane took a good form when it deflates.

Further Research:

According to the research result of fold detection analysis in new bladder design, it still needed to be completed by some of future research. They are:

1. The lifetime prediction comparison between first and new conceptual bladder design by considering how many times the fold structure forming in every cycle and the radius of fold.
2. The design development which take the safety factor into account of the bladder designer as the component will have dynamic loads during its operation.
3. The effect of temperature and temperature changing, because every sea in every side of the world has different temperature and also there is a changing of temperature based on the season. However, rubber, as the main material of the bladder membrane, is very sensitive with the temperature due to the transition from ductile to brittle.

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Appendix A

Rubber Properties

Various Rubber Properties

Table A. 1: Relative Properties of Various Rubber. Retrieved from (Harris, 2010)

ASTM designation	NR	BR	SBR	IIR CIIR	EPM EPDM	CSM	CR	NBR	HNBR	ACM ANM	T	FKM	FVMQ	VMQ MQ, PMQ, PVMQ	AU EU	GPO	CO ECO
Durometer range	30–90	40–90	40–80	40–90	40–90	45–100	30–95	40–95	35–95	40–90	40–85	60–90	40–80	30–90	35–100	40–90	40–90
Tensile max, psi	4500	3000	3500	3000	2500	4000	4000	4000	4500	2500	1500	3000	1500	1500	5000	3000	2500
Elongation max., %	650	650	600	850	600	500	600	650	650	450	450	300	400	900	750	600	350
Compression set	A	B	B	B	B-A	C-B	B	B	B-A	B	D	B-A	C-B	B-A	D	B-A	B-A
Creep	A	B	B	B	C-B	C	B	B	B	C	D	B	B	C-A	C-A	B	B
Resilience	High	High	Med.	Low	Med.	Low	High	Med.-Low	Med.	Med.	Low	Low	Low	High-Low	High-Low	High	Med.-Low
Abrasion resistance	A	A	A	C	B	A	A	A	A	C-B	D	B	D	B	A	B	C-B
Tear resistance	A	B	C	B	C	B	B	B	B	D-C	D	B	D	C-B	A	A	C-A
Heat aging at 212°F	C-B	C	B	A	B-A	B-A	B	B	A	A	C-B	A	A	A	B	B-A	B-A
T_g, °C	–73	–102	–62	–73	–65	–17	–43	–26	–32	–24, –54	–59	–23	–69	–127, –86	–23, –34	–67	–25, –46
Weather resistance	D-B	D	D	A	A	A	B	D	A	A	B	A	A	A	A	A	B
Oxidation resistance	B	B	C	A	A	A	A	B	A	A	B	A	A	A	B	B	B
Ozone resistance	NR-C	NR	NR	A	A	A	A	C	A	B	A	A	A	A	A	A	A
Solvent resistance																	
Water	A	A	B-A	A	A	B	B	B-A	A	D	B	A	A	A	C-B	C-B	B
Ketones	B	B	B	A	B-A	B	C	D	D	D	A	NR	D	B-C	D	C-D	C-D
Chlorohydrocarbons	NR	NR	NR	NR	NR	D	D	C	C	B	C-A	A	B-A	NR	C-B	A-D	A-B
Kerosene	NR	NR	NR	NR	NR	B	B	A	A	A	A	A	A	D-C	B	A-C	A
Benzol	NR	NR	NR	NR	NR	C-D	C-D	B	B	C-B	C-B	A	B-A	NR	C-B	NR	B-A
Alcohols	B-A	B	B	B-A	B-A	A	A	C-B	C-B	D	B	C-A	C-B	C-B	B	C	A
Water glycol	B-A	B-A	B	B-A	A	B	B	B	A	C-B	A	A	A	A	C-B	B	C
Lubricating oils	NR	NR	NR	NR	NR	A-B	B-C	A	A	A	A	A	A	B-C	A-B	D	A

A = excellent, B = good, C = fair, D = use with caution, NR = not recommended

Appendix B

EPDM Detail Properties

Rubber Material Selection Guide EPDM or Ethylene Propylene

▪ Abbreviation	EP, EPR, EPT, EPDM
▪ ASTM D-2000 Classification	AA, BA, CA, DA
▪ Chemical Definition	ethylene propylene diene
▪ RRP Compound Number Category	80000 Series

Physical & Mechanical Properties

▪ Durometer or Hardness Range	30 – 90 Shore A
▪ Tensile Strength Range	500 – 2,500 PSI
▪ Elongation (Range %)	100 % – 700 %
▪ Abrasion Resistance	Good
▪ Adhesion to Metal	Good to Excellent
▪ Adhesion to Rigid Materials	Good to Excellent
▪ Compression Set	Poor to Excellent
▪ Flex Cracking Resistance	Good
▪ Impact Resistance	Very Good
▪ Resilience / Rebound	Fair to Good
▪ Tear Resistance	Fair to Good
▪ Vibration Dampening	Fair to Good

Chemical Resistance

▪ Acids, Dilute	Excellent
▪ Acids, Concentrated	Excellent
▪ Acids, Organic (Dilute)	Excellent
▪ Acids, Organic (Concentrated)	Fair to Good
▪ Acids, Inorganic	Excellent
▪ Alcohol’s	Good to Excellent

Chemical Resistance

Aldehydes	Good to Excellent
Alkalies, Dilute	Excellent
Alkalies, Concentrated	Excellent
Amines	Fair to Good
Animal & Vegetable Oils	Good
Brake Fluids, Non-Petroleum Based	Good to Excellent
Diester Oils	Poor
Esters, Alkyl Phosphate	Excellent
Esters, Aryl Phosphate	Excellent
Ethers	Fair
Fuel, Aliphatic Hydrocarbon	Poor
Fuel, Aromatic Hydrocarbon	Poor
Fuel, Extended (Oxygenated)	Poor
Halogenated Solvents	Poor
Hydrocarbon, Halogenated	Poor
Ketones	Good to Excellent
Lacquer Solvents	Poor
LP Gases & Fuel Oils	Poor
Mineral Oils	Poor
Oil Resistance	Poor
Petroleum Aromatic	Poor
Petroleum Non-Aromatic	Poor
Refrigerant Ammonia	Good
Refrigerant Halofluorocarbons	R-12, R-13
Refrigerant Halofluorocarbons w/ Oil	Poor
Silicone Oil	Excellent
Solvent Resistance	Poor

Thermal Properties

▪ Low Temperature Range	- 60º F to - 40º F
▪ Minimum for Continuous Use (Static)	- 60º F
▪ Brittle Point	- 70º F
▪ High Temperature Range	+ 220º F to + 300º F
▪ Maximum for Continuous Use (Static)	+ 300º F

Environmental Performance

▪ Colorability	Good to Excellent
▪ Flame Resistance	Poor
▪ Gas Permeability	Fair to Good
▪ Odor	Good
▪ Ozone Resistance	Good to Excellent
▪ Oxidation Resistance	Excellent
▪ Radiation Resistance	Good to Excellent
▪ Steam Resistance	Excellent
▪ Sunlight Resistance	Excellent
▪ Taste Retention	Good to Excellent
▪ Weather Resistance	Excellent
▪ Water Resistance	Excellent