Burst Strength Analysis of Composite Pressure Vessel using Finite Element Method

by

Ho Yik Hong

15953

Dissertation submitted in partial fulfilment

of the requirement for the

Bachelor of Engineering (Hons)

Mechanical Engineering

JANUARY 2016

Universiti Teknologi PETRONAS

32610 Bandar Seri Iskandar

Perak Darul Ridzuan, Malaysia.

CERTIFICATION OF APPROVAL

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Approved by,

____

(Dr. Saravanan Karuppanan)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

January 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and the original work contained herein have not been undertaken or done by unspecified sources or persons.

(HO YIK HONG)

ABSTRACT

Currently, composite pressure vessels are widely utilized in industries like the oil and gas industry and etc. The demand for such vessels is constantly increasing due to their better strength properties than conventional metallic pressure vessels which are heavy and highly prone to corrosion. Thus, this prompts for a more cost effective and sustainable method to assess structural integrity of a composite pressure vessel which could minimize burst failures during operations. However, the main problems are the lack of literatures and research works for design optimization as well as the lack of defined materials for composite pressure vessel construction. Hence, the main objectives of this project are to perform burst failure analysis and to conduct parametric burst failure studies on composite pressure vessels using finite element method. The main scopes of this project are the adaptation of failure criteria like Tsai-Wu, Tsai-Hill and maximum stress in performing burst failure analysis as well as parametric studies on the optimal filament orientation angle and materials used for the liner and shell of a composite pressure vessel. The methodologies involved in this project is the employment of a benchmark model and the utilization of ANSYS-Composite-PrepPost (ANSYS-ACP) for the finite element analysis. In overall, the obtained burst pressure results from the simulation showed only a 10% difference with the benchmark results. Parametric studies also proved that optimal filament orientation angle to be $\pm 55^{o}$. Besides that, pressure vessel model with high density polyethylene (HDPE) liner was found to have better strength properties than those with S-Glass/Epoxy glass reinforced polymer liner and AL 6061 aluminium alloy liner, which allowed a burst pressure of 14.5 MPa. In another case study on shell materials, it was found that the pressure vessel model with T300/LY5052 carbon fiber reinforced polymer shell could sustain a burst pressure of 14.5 MPa, which is higher than another model with basalt/LY556 basalt fiber reinforced polymer shell. Besides that, pressure vessel model with a heterogeneous shell, showed a lower burst strength than the other vessel with a homogeneous shell. The last case study on strength-to-weight ratio also proved that the composite pressure vessel model that is made from T300/LY5052 carbon fiber reinforced polymer is 3 times lighter than an isotropic AL 6061 aluminium alloy pressure vessel of equivalent strength.

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LIST OF ABBREVIATIONS

ANSYS-ACP	ANSYS-Composite-PrepPost
ANSYS-ADPL	ANSYS parametric design language
ANSYS-ACP-Pre	ANSYS composite pre-processing
IRF	Inverse reserve factor
HDPE	High density polyethylene
CFRP	Carbon fiber reinforced polymer
BFRP	Basalt fiber reinforced polymer

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Composite pressure vessels, which are initially made exclusive for military and aerospace applications, have now slowly making its way into civilian commercial markets. Examples of highly commercialized composite pressure vessel based products include breathing aid devices, liquid or gas containment devices for various mechanical systems and etc [1-2]. Besides that, such filament wound composite pressure vessels have been widely employed in industries like the chemical industry, various power generation industries like the nuclear industry as well as the oil and gas industry [3-5]. In the oil and gas industry alone, the demand for composite pressure vessels is expected to increase by at least 10% in the next five years [6]. As for future market penetration, the industries that potentially have mass application for composite pressure vessels are the automotive industry and transportation industry as compatible storage vessels for either compressed natural gas (CNG) [1], or hydrogen (H_2) fuel cell are being developed [7-11]..

The reason behind the ever increasing demand for composite pressure vessels is that they out-perform conventional isotropic pressure vessels with refined characteristics like better mechanical properties, better strength-to-weight ratio, better fatigue resistance, better corrosion resistance as well as better thermal insulation, which enhances reliability [7-11]. By having a multilayer or orthotropic structure, composite pressure vessels could withstand higher operating pressure and temperature [3, 5], making it the best replacement for isotropic pressure vessels [2]. Hence, increased applications of composite pressure vessels have led to more extensive research work, especially on those newer Type IV and Type V models to provide a better understanding in terms of material properties, failure behaviour as well as to provide parametric studies for design, reliability and safety purposes [3, 5].

Therefore, using finite element analysis, failure phenomenon of a composite pressure vessel with high complexity could be simulated. For instance, composite laminate failure at microstructure level [8, 10], the exact burst pressure values, the location of burst failure [14], extensive composite laminate strength analysis [9] and etc, could be accurately modelled, simulated and predicted. Moreover, other dependent design parameters like the strength of selected materials, filament layers winding angle and thickness as well as other geometric variables could be optimized via the same approach [12]. Such factors would greatly influence the safety and reliability performance of the final product [9]. In another point of view, the use of finite element method for the burst failure analysis of composite pressure vessels would decrease the usage of experimental tests which are more expensive to perform [15].

As a conclusion, composite pressure vessels exist in various forms like reactors, separators, heat exchangers, tanks [3] and etc, where the composite components are subjected with high pressure and high stress levels during operations. Moreover, the vessels will be utilized in harsh environments and conditions as well [12]. Even though composite pressure vessels may have a simple outlook as well as a simple function, they are sometimes, hardest to design [13]. Therefore, most of the current research development in this context focuses on identifying the damage and failure behaviour of a composite pressure vessel [7].

1.2 Problem Statement

As aforementioned, pressure vessels are widely used in various industries and normally comes under the category of Type I or Type II where the shell of these pressure vessels are made up of metallic materials like carbon steel or aluminium alloy. These materials are highly prone to corrosion and weighs a lot heavier than composite materials like carbon fiber reinforced polymer and etc. Therefore, composite pressure vessels have became more common in application with increased demand due to their better material properties, increased durability, decreased corrosion rate as well as reduced equipment weight. Hence, these material advantages have prompted for more research work onto this subject.

The main problem of the composite pressure vessel application is the lack of literatures and research works that provide a clear approach in structural integrity assessment as well as design optimization of a composite pressure vessel [11, 15]. Thus, it is mandatory to develop more accurate ways to simulate burst failures of composite pressure vessels via finite element method in order to mitigate plausible burst failures which are normally caused by pressure overloading, fatigue and etc, in which could cause catastrophic effects to human and the environment [15].

Besides that, the other problem involved is the lack of a defined composite material that is made best for the construction of a composite pressure vessel. Therefore, further studies are required to identify or discover such composite materials in order to optimize the burst strength of a composite pressure vessel as well as the manufacturability of such composite pressure vessels.

1.3 Objectives

The main objectives of this project are:

i. To perform burst failure analysis of composite pressure vessels using finite element method and incorporating failure criteria like Tsai-Wu, Tsai-Hill, maximum stress, based on first ply failure.
ii. To perform parametric burst failure studies of composite pressure vessels using finite element method.

1.4 Scope of Study

The primary scope of this study is to develop the most suitable finite element method using software like ANSYS-Composite-PrepPost (ANSYS-ACP) and ANSYS Static Structural to simulate first ply burst failure of a composite pressure vessel, based on failure criteria like Tsai-Wu failure criterion, Tsai-Hill failure criterion, maximum stress failure criterion.

The next project study scope is to simulate and validate the burst failure of the pressure vessel model with dimensions and operational parameters obtained from referred literatures. In this context, the benchmark model is extracted from the research paper entitled "Finite Element Analysis of Filament-Wound Composite Pressure Vessel under Internal Pressure" by Sulaiman et al. [2].

Lastly, parametric studies on the modelled composite pressure vessel are to be done. This involves exploring parameters of the composite pressure vessel like optimal filament winding angle, liner and shell materials as well as strength-to-weight ratio of pressure vessel models with different built materials.

CHAPTER 2

LITERATURE REVIEW

2.1 Composite Pressure Vessel

In general, composite pressure vessels are mainly utilized under high stress and high pressure operating conditions and are constructed with an inner liner and multiple outer lamination shells [3]. The inner liner is normally made of metal alloys like AL 6061 aluminium alloy while the newer Type IV composite pressure vessels would have a liner made of high density polyethylene (HDPE) or other forms of polymer or thermoplastic. On the other hand, multiple layers of the outer load bearing shells are commonly made out of reinforced composite materials with high tensile strength [3], for example, carbon fiber and resin composites that are arranged in a polymeric epoxy matrix. Thus, the shell structure is considered orthotropic and the designed shape would normally be cylindrical [13]. With its multilayered construction, the composite pressure vessel ensures inbuilt safety, minimal material usage and requires no stress relief upon completion.

As aforementioned, the multilayered composite pressure vessels are created with a process where an inner liner is overlapped and cured with several layers of high strength composites, to serve the purpose of vessel quality assurance and properties optimization [3]. Hence, to fabricate such complex composite structures, the technique a manufacturer would normally endorse is the filament winding process in which fiber filaments are continuously wounded on supporting mandrel with or without the core tube attached on it. During the whole process, the mandrel will rotate along with the spindle on one axis horizontally, with the carriage moving on another in the linear direction where the composite layers are laid accordingly to the desired winding angle [2, 11]. Moreover, design flexibility like varying laminate ply number, applying layers with different thickness, changing ply orientation and etc, enables adaptation of various ply stacking patterns and geometry parameters [8].

2.2 Optimal Lamination Orientation Angle

As aforesaid, one of the main factors to achieve the optimum stiffness and strength of a composite pressure vessel is to deploy or lay the unidirectional composite shell layers on the liner with optimized filament winding angle orientation as well as via hoop and helical winding methods [4, 7].

This reason is that the subjected structural stresses and strain of a composite pressure vessel is greatly affected not just by the laminations' stacking sequence and thicknesses, but the orientation angle as well [17]. It was found that, under different lamination orientation angle, the composite pressure vessel's hoop to axial stress ratio deviates accordingly, and is not a constant of two [15, 17]. On top of that, the strain ratio or the hoop to axial stress ratio is also found to increase when the shell lamination is oriented in the circumferential direction and decreases when it aligns in the axial direction [15, 18].

On the other hand, via theoretical calculations as well as netting analysis, the optimal shell lamination orientation angle for a composite pressure vessel was found to be 54.74^{o} [1-2, 19]. Besides that, it was also discovered that the burst failure pressure would be increased if the composite pressure vessel's shell lamination is oriented under varying angle as well as in a symmetrical order [2, 19].

2.3 Types and Classifications

Currently, there are 5 different types of composite pressure vessels being developed in the market which are Type I, II, III, IV and V respectively. Table 2.1 explains about the differences between all the 5 types of vessels [16, 20].

Table 2.1: Types of Pressure Vessel

Type	Description
I	The pressure vessel is solely constructed with isotropic metallic materials. The vessel has no inner liner and outer lamination.
II	The pressure vessel construction is similar to the Type I isotropic pressure vessel, but with a thin outer fiber-resin composite shell wrapping the vessel's hoop section.
III	The pressure vessel has an orthotropic structure where it has an inner metallic liner and outer fiber-resin composite shell.
IV	The pressure vessel has a non metallic liner, made up of high density polyethylene (HDPE) or other equivalent polymers with a multilayered outer shell made of fiber-resin composite plies.
V	The pressure vessel is similar to a Type IV composite pressure vessel, but without an inner liner.

Currently, Type IV and Type V composite pressure vessels are considered as to have better designs [16]. As compared to a Type III composite pressure vessel, the Type IV and Type V composite pressure vessels would have equivalent or better strength properties even though the vessels' shells are thinner, which made them more cost effective to be manufactured [21]. In both Figure 2.1 and Figure 2.2, the major differences between the Type III and the Type IV pressure vessels in terms of structural layout as well as the material usage are clearly shown [21].

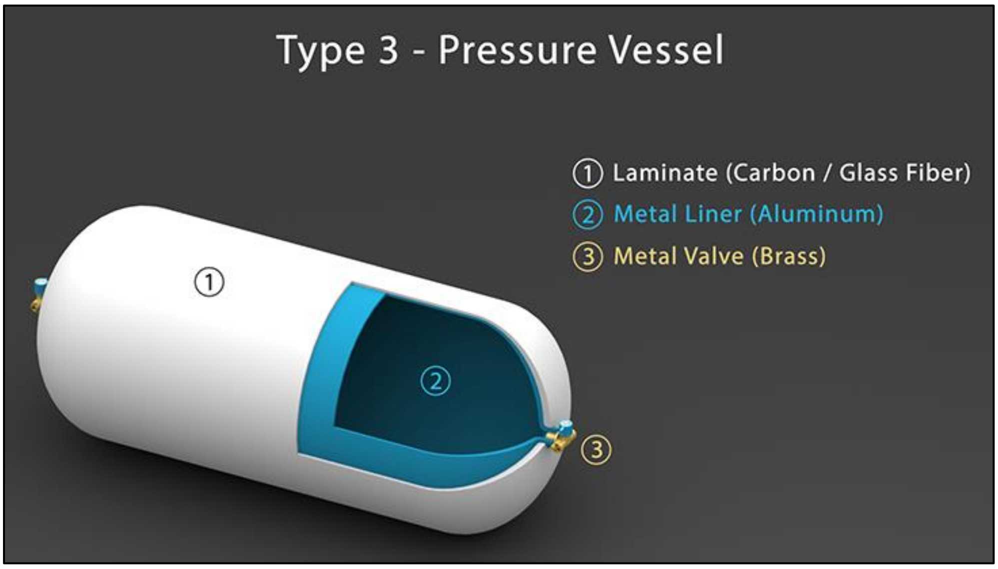

Figure 2.1: Type III Composite Pressure Vessel [21]

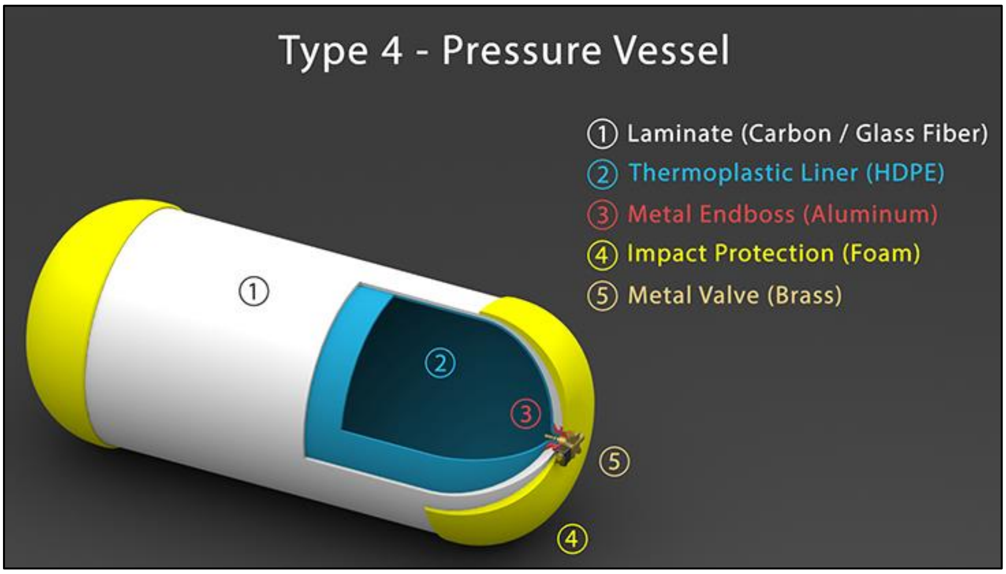

Figure 2.2: Type IV Composite Pressure Vessel [21]

In another context, a composite pressure vessel could be categorized as either a thin or thick walled vessel. In a thick walled pressure vessel, the ratio between the pressure vessel's outer shell diameter and inner shell diameter should be larger than 1.1. On the other hand, if the ratio between the outer shell diameter and the inner shell diameter is below the value of 1.1, the composite pressure vessel would be classified as a thin walled pressure vessel [2, 3, 14].

2.4 Finite Element Method

As mentioned previously, finite element method allows modelling and simulation of a multilayered composite pressure vessel for burst strength capacity determination. However, orthotropic composite structures require complex definitions as it involves multilayer structures, varying materials, thicknesses and orientations [22]. Besides that, the finite element analysis would also take into account of the model's stresses, deformation as well as failure criteria like maximum stress failure criterion, Tsai-Wu failure criterion and Tsai-Hill failure criterion [23].

On top of that, an orthotropic composite structure is normally modelled using shell elements but that will become inappropriate when the involved finite element model is large in size, for instance, a composite pressure vessel where subjected stresses in the direction of thickness and shear stresses out of plane are significant [23]. Thus, solid models are more suitable in this case. Besides that, solid models are required as well when loads are to be applied in the direction of the vessel thickness or when the simulation is structurally subjected to deformations [23].

Therefore, ANSYS Workbench and ANSYS Composite PrepPost (ANSYS-ACP) are the most suitable finite element software to be used as they are capable of all the aforesaid mandatory functionalities for the analysis of an orthotropic composite structure like the composite pressure vessel [22].

2.5 Failure Analysis Method

There are abundance of failure analysis method failure criteria that has the function to estimate failure properties of an orthotropic composite structure. However, there are 2 categories in general, which are the independent criterion and interactive criterion [13, 24]. The differences between both types are shown in Table 2.2 below.

Table 2.2: Types of Failure Analysis Criterion

Criteria	Description
Independent	The application of such method to detect failure is simple and significant but it lacks of stress interactions detection between each lamina [13]. Examples of independent criteria are the maximum stress and strain failure criterion [24].
Interactive	The stress interactions in lamina failure mechanism are included, enabling failure predictions on the lamination plies of an orthotropic structure [13]. However, parameters and properties must be clearly and accurately input. Examples of interactive criteria are Tsai-Wu failure criterion, Tsai-Hill failure criterion, Hoffman failure criterion [24].

In general, the failure criteria that are suitable to be endorsed in the burst failure finite element analysis are Tsai-Wu failure criterion, Tsai-Hill failure criterion, maximum stress failure criterion and maximum strain criterion. These criteria are able to produce results with an acceptable degree of accuracy [2, 25-26].

On the other hand, the failure of the orthotropic composite model would normally be based on first ply failure or last ply failure as all the plies in an orthotropic structure would be subjected to failure in a sequence, which would result in ultimate failure [27]. The more conservative first ply failure is considered as the most appropriate to evaluate burst failure of a composite pressure vessels as the structures are constantly subjected to high internal pressure and can only tolerate zero damage [19, 27].

2.5.1 Tsai-Wu Failure Criterion

Tsai-Wu failure criterion is a quadratic, interactive stress based failure criterion [28]. Tsai-Wu failure criterion uses equation (1) for failure prediction of orthotropic lamina under plane stress condition [2, 9, 13]. Since Tsai-Wu failure criterion portrays versatility where it could be used in all quadrants of a stress plane as well as in 3 dimensional situations without major modification, Tsai-Wu failure criterion is considered as one of the most conservative and accurate failure criterion [9-10].

$$F_{11}\sigma_1{}^2 + F_{22}\sigma_2{}^2 + F_{66}\tau_{12}{}^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 \geq 1 \quad (1)$$

where,

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c}$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c}$$

$$F_{11} = \frac{1}{X_t X_c}$$

$$F_{22} = \frac{1}{Y_t Y_c}$$

$$F_{66} = \frac{1}{S^2}$$

$$F_{12} = \frac{1}{2}\sqrt{F_{11}F_{22}}$$

X_t = longitudinal tensile strength
Y_t = transverse tensile strength
X_c = longitudinal compressive strength
Y_c = transverse compressive strength
S = in-plane shear strength

2.5.2 Tsai-Hill Failure Criterion

Using the similar mode of analysis as the Tsai-Wu failure criterion, Tsai-Hill failure criteria could be represented with the following equation (2) [2]:

$$F_{11}\sigma_1{}^2 + F_{22}\sigma_2{}^2 + F_{66}\tau_{12}{}^2 + 2F_{12}\sigma_1\sigma_2 \geq 1 \quad (2)$$

where,

$$F_{11} = \frac{1}{X^2}$$

$$F_{22} = \frac{1}{Y^2}$$

$$F_{66} = \frac{1}{S^2}$$

$$F_{12} = -\frac{1}{2}(\frac{1}{X^2} + \frac{1}{Y^2})$$

X = longitudinal tensile strength

Y = transverse tensile strength

S = in-plane shear strength

2.5.3 Maximum Stress Failure Criterion

Maximum stress failure criterion is able to detect failure by comparing the acquired maximum principle stress with the ultimate stress or the limiting allowable stress of the composite pressure vessel's built material as shown in equation (3) [2-5, 29]. Besides that, failure could also be considered if one of the following criteria is met as shown in equation (4) [2, 29].

$$\sigma_{max} \leq \sigma_u \qquad (3)$$

$$\left|\frac{\sigma_1}{X}\right| \geq 1\,, \left|\frac{\sigma_2}{Y}\right| \geq 1\,, \left|\frac{\sigma_3}{Z}\right| \geq 1 \qquad (4)$$

where,

σ_{max} = maximum stress during simulation;
σ_u = ultimate stress of pressure vessel

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

The overall execution plan of this project could be summarized via a project flow chart as shown in Figure 3.1. The scheduling for the project execution is shown in the project's Gantt Chart in Table 3.1.

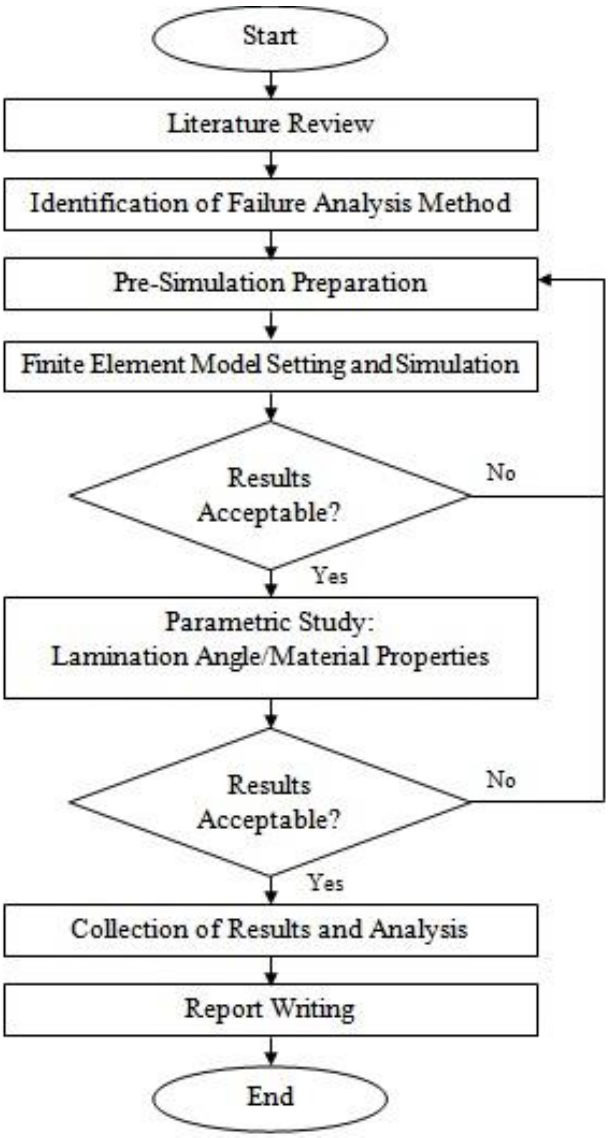

Figure 3.1: Project Flow Chart

Table 3.1: Project Gantt Chart and Key Milestones

No.	Activities	Weeks in FYP 1														Weeks in FYP 2													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review																											Δ	
2	Identification of Failure Analysis Method									Δ																			
3	Preparation for Referred Benchmark Model										Δ																		
4	Modelling/Simulation and Results Validation														Δ														
5	Parametric Study (Material/ Lamination Angle)																		Δ										
6	Modelling/Simulation and Results Comparison																				Δ								
7	Further Analysis and Validation of Results																												
8	FYP Report Writing																											Δ	

Δ : Key Milestone

3.1.1 Literature Review

Through various sources, vital information about the burst failure analysis of composite pressure vessels will be searched and referred. Examples of such would either be the methodologies and analytical data from previous research works which would aid the understanding of the project's fundamentals.

3.1.2 Identification of Failure Analysis Method

The modes of failure analysis for the burst strength will be set to be maximum stress failure criterion, Tsai-Hill failure criterion and Tsai-Wu failure criterion. Besides that, a more conservative first ply failure condition will be applied for the burst failure analysis. The lowest burst pressure obtained from either of the mentioned failure criteria would be considered as the pressure vessel's burst pressure.

3.1.3 Finite Element Modelling and Failure Analysis Simulation

For this project, the benchmark model is from the research paper entitled **"Finite Element Analysis of Filament-Wound Composite Pressure Vessel under Internal Pressure"** by Sulaiman et al. The model features a type III composite pressure vessel with an Al-6061 aluminium alloy liner and 6 T300/LY5052 carbon fiber reinforced polymer plies laid above the AL 6061 aluminium alloy liner. The cross sectional view of the benchmark model is as shown in Figure 3.2 [2].

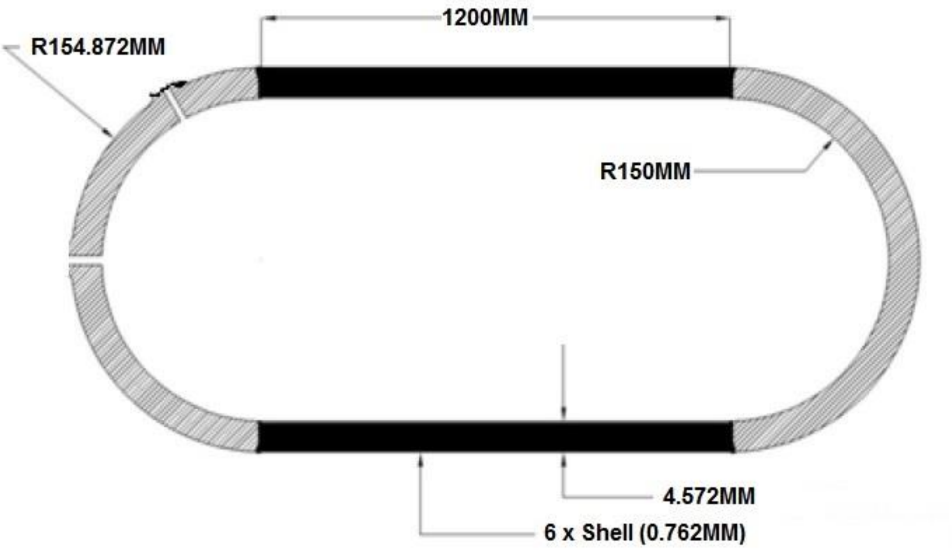

Figure 3.2 : Cross Sectional View of The Benchmark Model

Accordingly to the given dimension and material properties, the benchmark Type III composite pressure vessel would be first modelled via ANSYS Composite Pre-processing (ANSYS-ACP-Pre). Using the same component system, the pressure vessel model will be meshed with a global meshing size of 0.01 and Quad-dominated meshing type [2]. The shell and lamination stacking sequence is then assigned to the model, along with their material type, material properties and layer thickness. Table 3.2, Table 3.3 and Table 3.4 show the material properties for both the aluminium alloy liner and carbon fiber composite shell as well as their layout respectively.

After all the required pre-processing steps are done, the data from the ANSYS-ACP-Pre is then exported to another analysis system, ANSYS Static Structural, to assign internal load to the model. Here, constant pressure is applied to the inner wall of the pre-assigned pressure vessel model to generate solution values like equivalent stress, equivalent strain and total deformation. Starting from 2.0 MPa, incremental load will be applied onto the vessel until burst failure happens.

To identify burst failure, the results from ANSYS Static Structural must again, be exported to ANSYS Composite Post-processing (ANSYS-ACP-Post), where failure criteria like Tsai-Wu failure criterion, Tsai-Hill failure criterion and maximum stress failure criterion could be defined and applied onto the pressure vessel model. Using the post-processing system and failure criteria, the inverse reserve factor (IRF) values for each ply of the composite pressure vessel could be identified. Shall any element point on any of the plies has an IRF value of equal or more than 1.0 (IRF ≈ 1.0), first ply burst failure is considered to have occurred on the pressure vessel where the applied internal pressure is then be recognized as the burst pressure. Figure 3.3 shows the overall ANSYS analysis system layout.

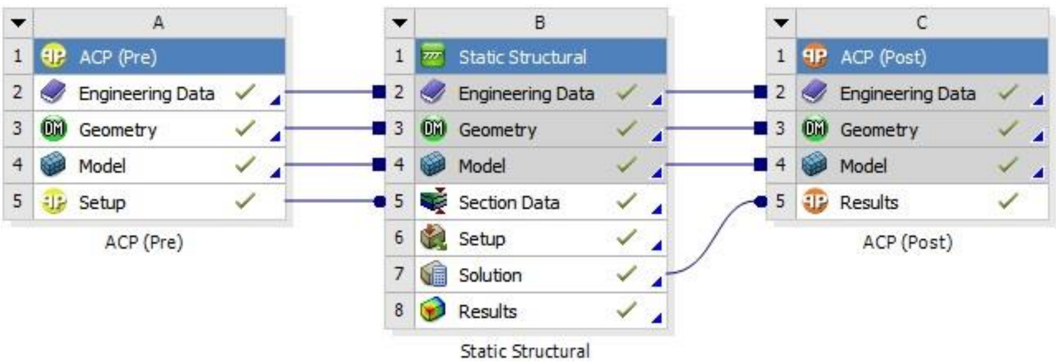

Figure 3.3 ANSYS Analysis System

Table 3.2: Properties of the T300/LY5052 Carbon Fiber Reinforced Polymer Ply

T300/LY5052 Material Properties	**Values**
Ply Type	Woven
Density	1570 kg/m^3
Orthotropic Elasticity	
Young's Modulus in X Direction (E_x)	135.00 GPa
Young's Modulus in Y & Z Direction ($E_y = E_z$)	8.00 GPa
Shear Modulus XY & XZ ($G_{xy} = G_{xz}$)	3.80 GPa
Shear Modulus YZ (G_{yz})	2.69 GPa
Poisson's Ratio XY & XZ ($P_{xy} = P_{xz}$)	0.27
Poisson's Ratio YZ (P_{yz})	0.49
Orthotropic Stress Limits	
Tensile Strength (X_t)	1860 MPa
Transverse Tensile Strength (Y_t)	76 MPa
Compressive Strength (X_c)	1470 MPa
Transverse Compressive Strength (Y_c)	85 MPa
Shear Strength (S)	98 MPa
Tsai-Wu Constants	
Coupling Coefficient XY	-1
Coupling Coefficient YZ	-1
Coupling Coefficient XZ	-1

Table 3.3: Properties of the AL 6061 Aluminium Alloy Liner Ply

AL 6061 Material Properties	**Values**
Ply Type	Isotropic
Density	2770 kg/m^3
Isotropic Elasticity	
Young's Modulus (*E*)	71.00 GPa
Bulk Modulus (*K*)	69.60 GPa
Shear Modulus (*G*)	26.70 GPa
Poisson's Ratio	0.33
Isotropic Stress & Strain Limits	
Yield Tensile Strength (X_t)	280 MPa
Yield Compressive Strength (X_c)	280 MPa
Ultimate Tensile Strength	310 MPa
Ultimate Compressive Strength	310 MPa
Elongation When Break	0.12

From the above sections, it is noticed that the initial model used is a Type III composite pressure vessel rather than a Type IV composite pressure vessel. The reason behind it is to allow comparison between both of these composite pressure vessel types in terms of structural integrity and failure mode. Another factor is because of the limited analytical data of the burst failure of a Type IV composite vessel that is to be referred in this context.

3.2 Parametric Studies

As the initial modelling as well as simulation is completed with the results validated by using ANSYS-ACP and ANSYS Static Structural, various parametric studies are to be carried out to further explore the strength properties of a composite pressure vessel under different design conditions. Below are the proposed case studies.

3.2.1 Optimal Filament Orientation Angle Study

This parametric study is where alterations on the pressure vessel's filament winding angle are made. The lamination angles that are to be assigned to the composite pressure vessel model are 0^o, $\pm15^o$, $\pm25^o$, $\pm35^o$, $\pm45^o$, $\pm55^o$, $\pm65^o$, $\pm75^o$, $\pm90^o$ respectively. The burst pressure values of all the parametric models will then be tabulated into a graph . Comparisons will then be done to identify the nominal filament orientation angle of the composite pressure vessel as well as to validate results from the referred research journals. Any deviations between the simulation results and the referred research papers' analytical data will be scrutinized.

Similarly, failure analysis methods like the Tsai-Wu failure criterion, Tsai-Hill failure criterion, maximum stress failure criterion, based on first ply failure shall be utilized to identify burst pressure of the modelled composite pressure vessel.

3.2.2 Liner Material Type Study

As the benchmark model uses a metal alloy liner, the benchmark model's pressure vessel is categorized as a Type III composite pressure vessel. Thus, to further conduct stress analysis on a Type IV composite pressure vessel, other types of liners shall be integrated to the benchmark model for burst failure analysis.

The types of liner materials utilized in this case study are AL 6061 aluminium alloy, S-Glass/Epoxy glass fiber reinforced polymer and high density polyethylene (HDPE). The liner material properties are listed in Table 3.3, Table 3.4, Table 3.5 respectively.

Table 3.4 Properties of High Density Polyethylene (HDPE) Ply

HDPE Material Properties	**Values**
Ply Type	Isotropic
Density	950 kg/m^3
Isotropic Elasticity	
Young's Modulus (E)	1.10 GPa
Bulk Modulus (K)	2.29 GPa
Shear Modulus (G)	3.87 GPa
Poisson's Ratio	0.42
Isotropic Stress & Strain Limits	
Yield Tensile Strength (X_t)	25 MPa
Yield Compressive Strength (X_c)	25 MPa
Ultimate Tensile Strength	33 MPa
Ultimate Compressive Strength	33 MPa
Elongation When Break	> 10

Table 3.5 Properties of S-Glass/Epoxy Glass Fiber Reinforced Polymer Ply

S-Glass/Epoxy Material Properties	**Values**
Ply Type	Regular
Density	2000 kg/m^3
Orthotropic Elasticity	
Young's Modulus X Direction (E_x)	50 GPa
Young's Modulus Y & Z Direction ($E_y = E_z$)	8.00 GPa
Shear Modulus XY & XZ ($G_{xy} = G_{xz}$)	5.00 GPa
Shear Modulus YZ (G_{yz})	3.85 GPa
Poisson's Ratio XY & XZ ($P_{xy} = P_{xz}$)	0.30
Poisson's Ratio YZ (P_{yz})	0.40
Orthotropic Stress Limits	
Tensile Strength (X_t)	1700 MPa
Transverse Tensile Strength (Y_t)	35 MPa
Compressive Strength (X_c)	1000 MPa
Transverse Compressive Strength (Y_c)	120 MPa
Shear Strength (S)	80 MPa
Tsai-Wu Constants	
Coupling Coefficient XY	-1
Coupling Coefficient YZ	-1
Coupling Coefficient XZ	-1

3.2.3 Shell Material Type Study

As aforementioned, the benchmark model utilized a T300/LY5052 carbon fiber reinforced polymer shell. However, as part of the parametric study, different types of composite materials are to be included into the burst failure analysis simulation to compare strength properties among the selected composite materials. The involved shell materials are T300/LY5052 carbon fiber reinforced polymer and Basalt/LY556 basalt fiber reinforced polymer. Table 3.2 in the previous section 3.1.3 showed the material properties for T300/LY5052 carbon fiber reinforced polymer while Table 3.5 below shows the material properties for Basalt/LY556 basalt fiber reinforced polymer [15]. Using the same finite element analysis approach and failure criteria, the composite pressure vessel model with a higher burst pressure will prove that the shell material used in that model has better strength properties than the rest.

As the aforementioned, a composite pressure vessel shell that is assigned only with one type of material is considered to be a homogeneous shell. Therefore, this parametric study also includes a composite pressure vessel model with a heterogeneous shell where both of the T300/LY5052 carbon fiber reinforced polymer and Basalt/LY556 basalt fiber reinforced polymer are laid in a alternating manner on top of the high density polyethylene (HDPE) liner. The burst pressure of this composite pressure vessel model with a heterogeneous shell is then to be simulated using the identical approach and compared with the previously acquired burst pressure results of models with homogeneous shell.

Table 3.5: Properties of the Basalt/LY556 Basalt Fiber Reinforced Polymer Ply

Basalt/LY556 Material Properties	**Values**
Ply Type	Woven
Density	1830 kg/m^3
Orthotropic Elasticity	
Young's Modulus X Direction (E_x)	38.90 GPa
Young's Modulus Y & Z Direction ($E_y = E_z$)	7.47 GPa
Shear Modulus XY & XZ ($G_{xy} = G_{xz}$)	2.71 GPa
Shear Modulus YZ (G_{yz})	2.54 GPa
Poisson's Ratio XY & XZ ($P_{xy} = P_{xz}$)	0.28
Poisson's Ratio YZ (P_{yz})	0.46
Orthotropic Stress Limits	
Tensile Strength (X_t)	1220 MPa
Transverse Tensile Strength (Y_t)	62.10 MPa
Compressive Strength (X_c)	780 MPa
Transverse Compressive Strength (Y_c)	93.10 MPa
Shear Strength (S)	85.70 MPa
Tsai-Wu Constants	
Coupling Coefficient XY	-1
Coupling Coefficient YZ	-1
Coupling Coefficient XZ	-1

3.2.4 Strength-to-Weight Ratio Analysis

This parametric study involves the modelling of a Type I isotropic pressure vessel that has the same burst strength properties as the previously modelled Type IV composite pressure vessel. Using the same inner dimension as the composite pressure vessel model, an isotropic metallic shell that is made up of AL 6061 aluminium alloy is to be assigned and simulated with the same maximum internal pressure that is acquired in the previous parametric studies.

To identify burst failure as well as location of failure, isotropic failure criteria is applied to the isotropic pressure vessel model. Shall the simulated model failed when is subjected to the constant internal pressure, thickness of the metallic shell will be increased until the inverse reserve factor (IRF) is less than or equal to 1.0. Once the isotropic pressure vessel model of the equivalent strength is modelled, the weights of both the Type I isotropic pressure vessel and the Type IV composite pressure vessel are to be calculated and compared in a ratio form.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Geometry and Layout of the Model

The pressure vessel model considered for finite element analysis in this project is a full scale (1:1) replica of the original benchmark model. In overall, there are 2 materials involved in the initial validation simulation which are AL 6061 aluminium alloy and T300/LY5052 carbon fiber reinforced polymer respectively. Properties of both materials, as mentioned before in Tables 3.2 and 3.3, are included in the simulation software's engineering data library. As for the ANSYS-ACP-Pre pre-processing setup, the aluminium alloy liner is assigned with isotropic properties and the carbon fiber/epoxy shell with orthotropic properties as shown in Figure 4.1. Then, the model is constructed via ANSYS-Geometry as shown in Figure 4.2.

To model the inner liner and the outer shell of the pressure vessel, the 7 liner and shell layers of the pressure vessel is input with individual layer thicknesses and material assignment. The overall view of the orthotropic structure is shown in Figure 4.3. As for the lamination angle, it is set initially to be ±55^{o} as shown in Figure 4.4.

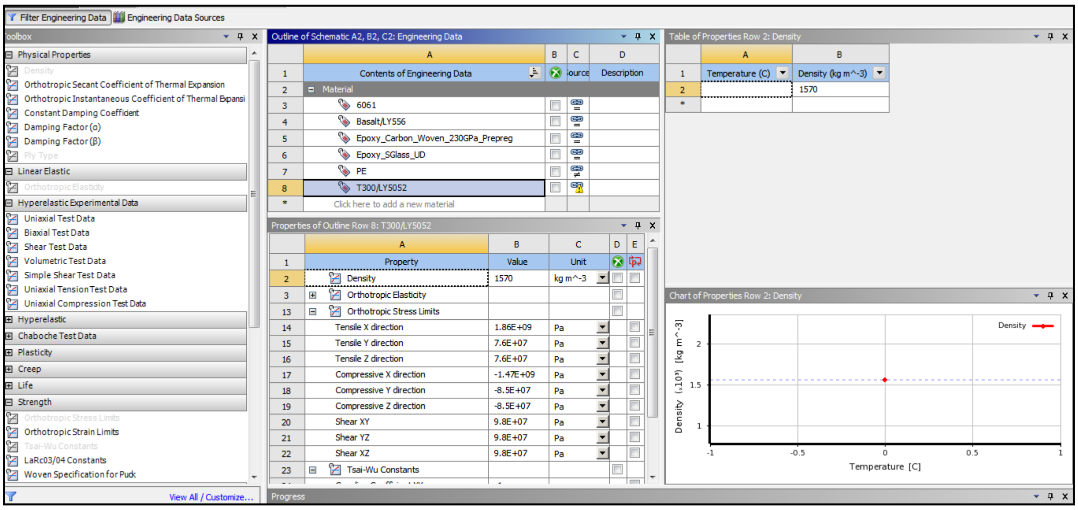

Figure 4.1 ANSYS Engineering Data Library

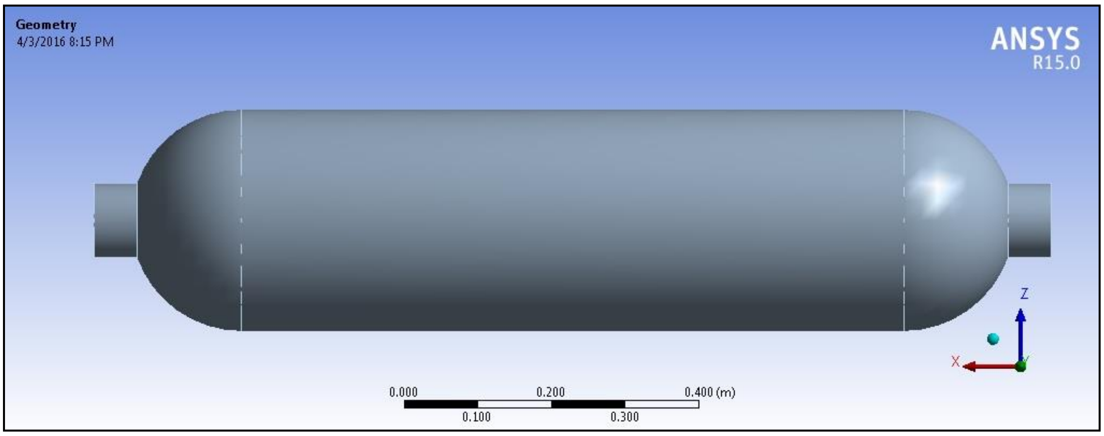

Figure 4.2: Modelling of Benchmark Model

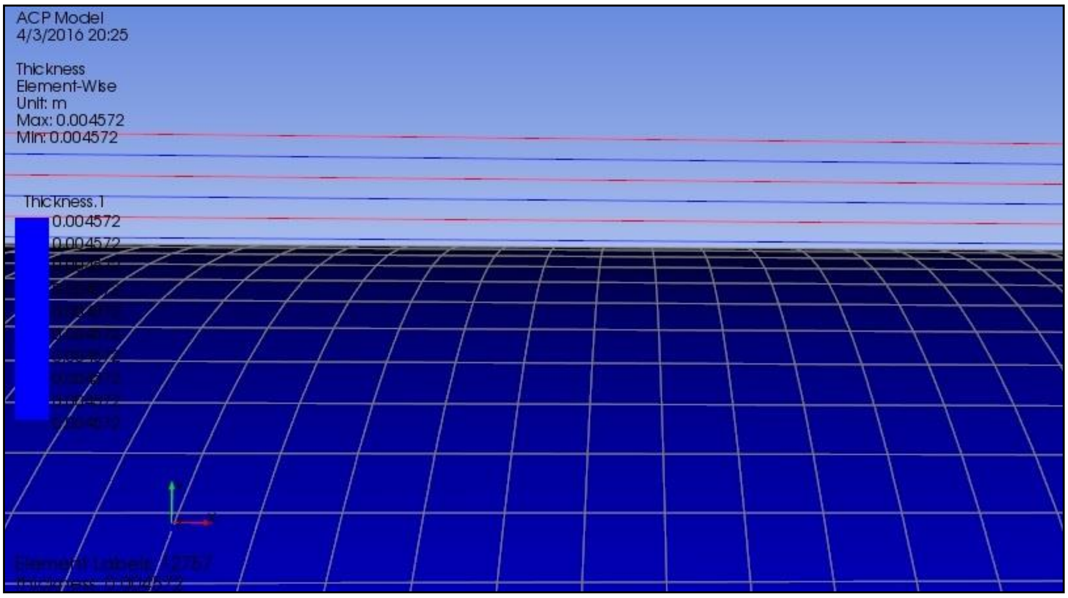

Figure 4.3: Liner and Shell Layers of the Model

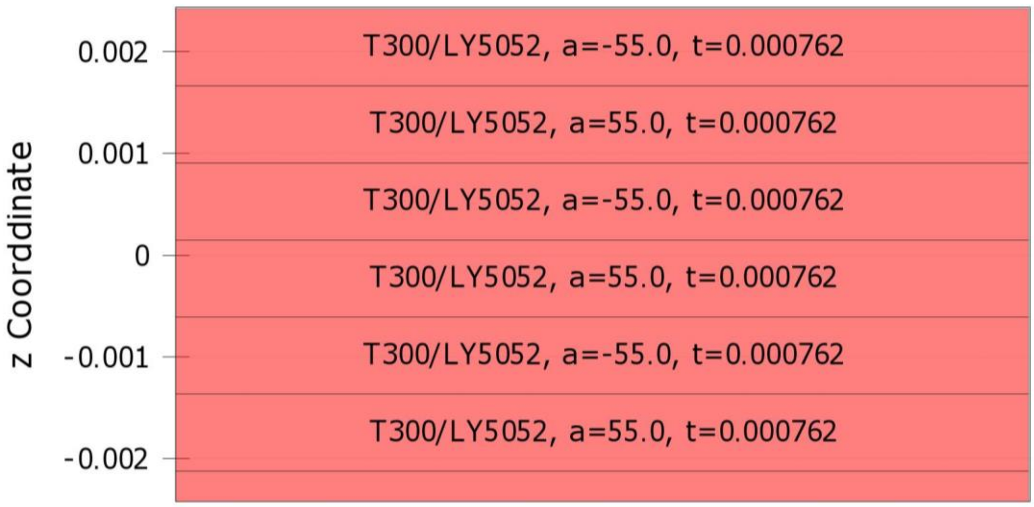

Figure 4.4: Lamination Layout of the Benchmark Model

4.2 Meshing of the Model

In the simulation of the initial benchmark model, disregarding the increased calculation time, the meshing properties are set at a finer level with a global meshing size of 0.01 to increase the accuracy of the simulation. The meshed benchmark model is portrayed in Figure 4.5 below, while the settings and acquired details of the meshing is as shown in Table 4.1 below.

Table 4.1: Properties of the Model's Meshing

Meshing Properties	Values/Description
Relevance Center	Fine
Smoothing & Span Angle Center	High
Mapped Face Meshing & Refinement	Enabled
Minimum Size	0.01
Maximum Face Size	0.01
Number of Nodes	19110
Number of Elements	19012

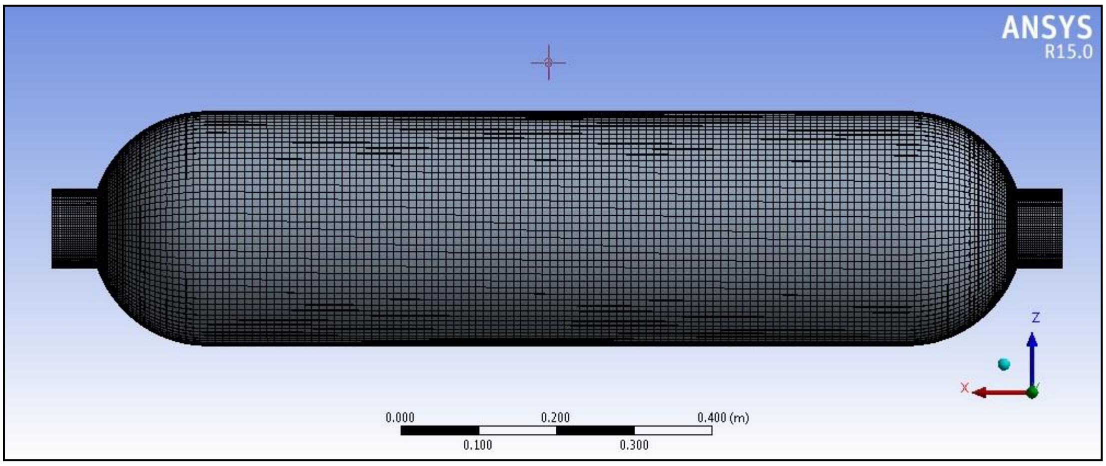

Figure 4.5: Meshed Benchmark Model

4.3 Initial Simulation Results

The initial burst failure simulation of the benchmark pressure vessel model is able to handle a maximum internal pressure of approximately 6.9 MPa as shown in Figure 4.6 before it sustains burst failure. The equivalent or Von Mises stress that the pressure vessel is subjected at that moment is 295.3 MPa as shown in Figure 4.7.

Using Tsai-Wu failure criterion, Tsai-Hill failure criterion and maximum stress criterion, the first ply failure is identified to happen at the AL 6061 aluminium liner, as shown in Figure 4.8 and Figure 4.9. With a maximum inverse reserve factor (IRF) of 1.0, the benchmark composite pressure vessel model is considered to have undergone burst failure. Besides that, the location where failure occurs is at the transition point between the pressure vessel's hoop segment and dome segment.

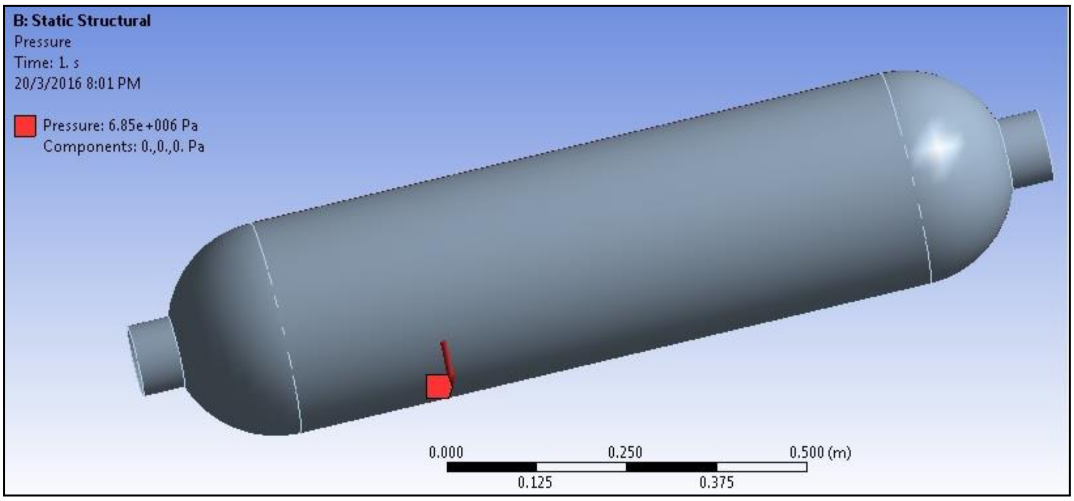

Figure 4.6: Benchmark Model with a Pressure Load of 6.9 MPa

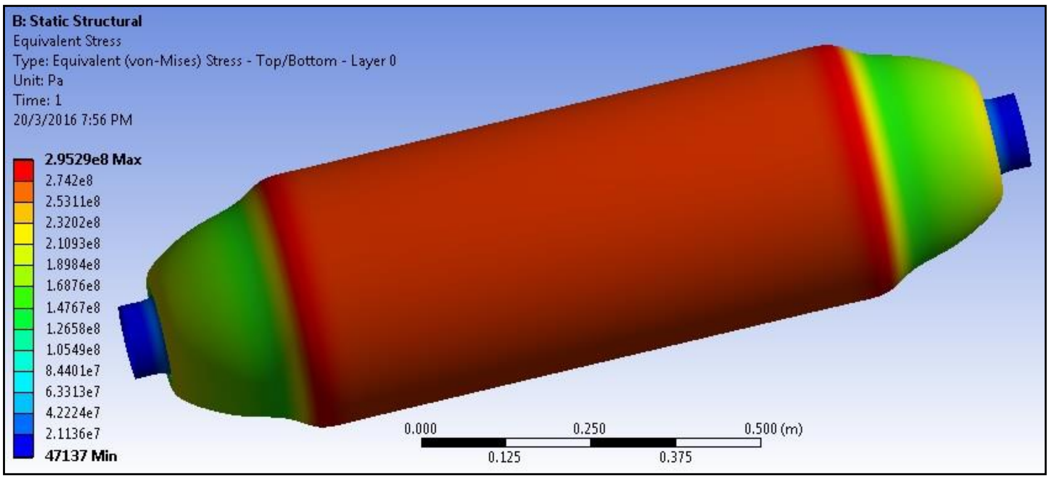

Figure 4.7: Subjected Equivalent Von Mises Stress at Burst Failure

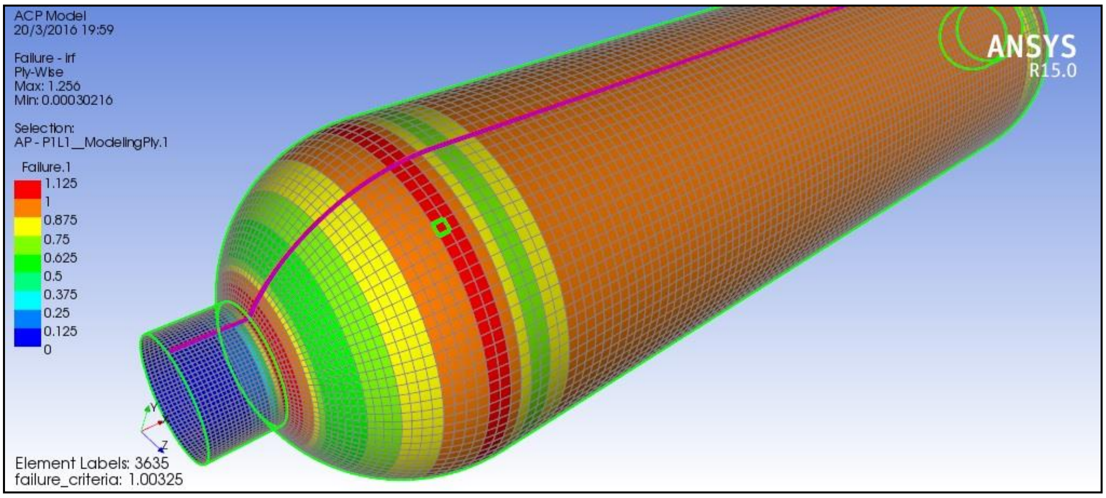

Figure 4.8: Inverse Reverse Factor (IRF) and Failure Point of the Benchmark Model

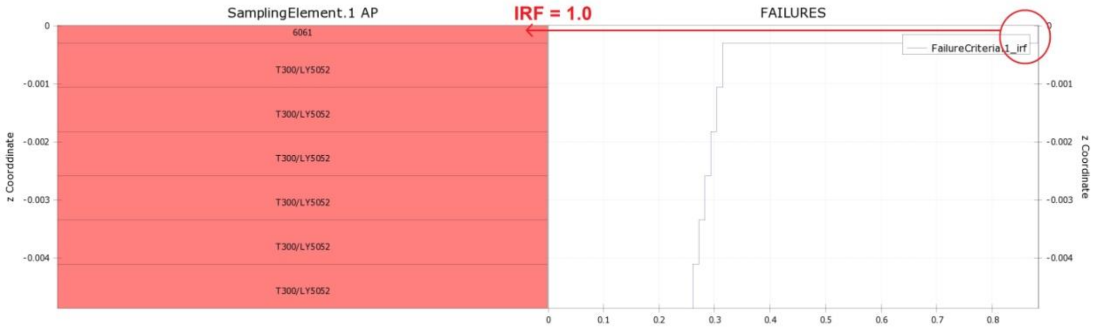

Figure 4.9: Inverse Reserve Factor (IRF) of Each Lamination Layer

However, as quoted in the referred journal, the burst pressure of the benchmark model should be 15.5 MPa [2]. Thus, the benchmark model's burst pressure is so much higher than the initial burst pressure result of 6.9 MPa, which shows a percentage error of 55.5% as shown in equation (5).

$$Percentage\ Error\ (\%) = \left|\frac{Benchmark - Acquired}{Benchmark}\right| \times 100\% \quad (5)$$

$$Percentage\ Error\ (\%) = \left|\frac{15.5 - 6.9}{15.5}\right| \times 100\% = 55.5\%$$

This showed a large deviation of burst pressure values between the project model and the benchmark model. Therefore, an revised edition of the benchmark model shall be simulated to further investigate the high percentage error of 55.5% which is unacceptable in terms of result validation.

4.4 Revised Simulation Results

As aforementioned in previous section, the percentage error between the project model and the benchmark model is at 55.5% and thus, a simulation iteration of the benchmark model without the inner liner layer is to be done using the same approach to investigate the high results deviation.

Therefore, as shown in Figure 4.10, the lamination layout of the modified benchmark model is assigned to have only 6 layers of the T300/LY5052 carbon fiber reinforced polymer and without a liner. Similar to the initial model, the lamination angle is set at $\pm 55^{o}$ for optimal structural integrity [1, 2].

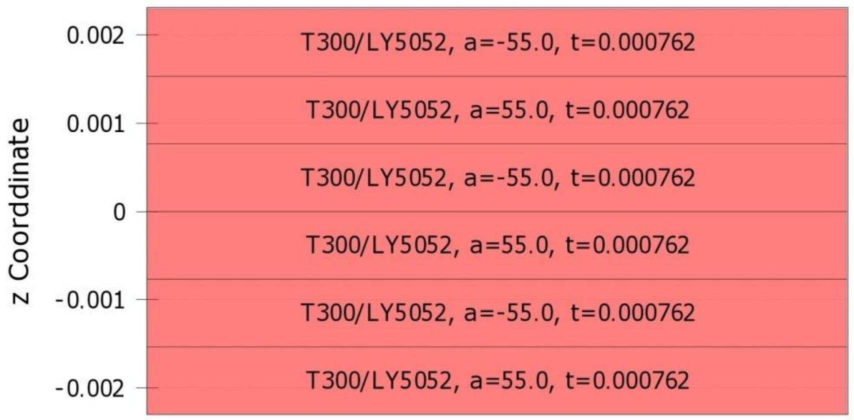

Figure 4.10: Lamination Layout of the Benchmark Model Without Liner

After slight modifications, the linerless benchmark model with a lamination angle of $\pm 55^{o}$ is able to handle a maximum internal pressure of approximately 13.8 MPa as shown in Figure 4.11 and is subjected to an equivalent stress of 643.3 MPa as shown in Figure 4.12. Shown in Figure 4.13, with an inverse reserve factor (IRF) of 1.0, first ply failure happened at the first, most bottom carbon fiber reinforced polymer layer while structural failure happened at the dome and hoop intersection. Using equation (5) from section 4.3 above, a percentage error of 10.0% was found. Hence, the benchmark results are considered validated and is concluded that no liner was included in the benchmark model's burst failure analysis.

Therefore, for the upcoming parametric study of the optimal shell lamination angle, a model without liner should be used to produce results of higher accuracy.

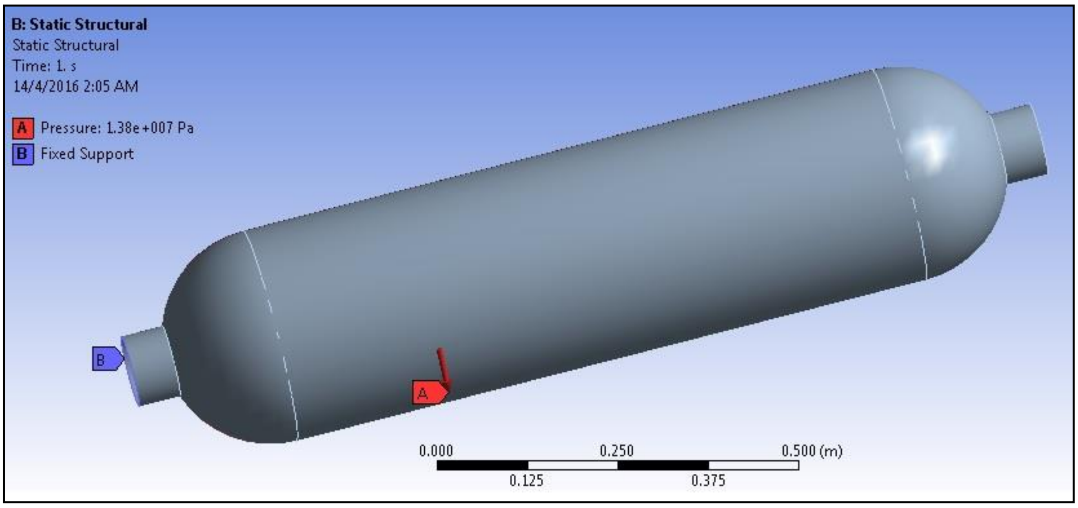

Figure 4.11: Modified Benchmark Model with internal pressure load of 13.8 MPa

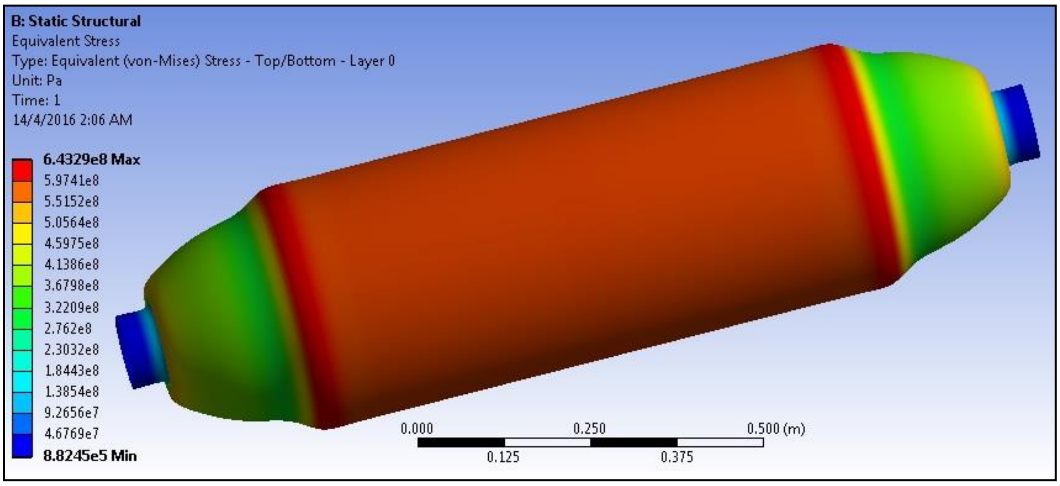

Figure 4.12: Subjected Stress of Modified Benchmark Model at Burst Failure

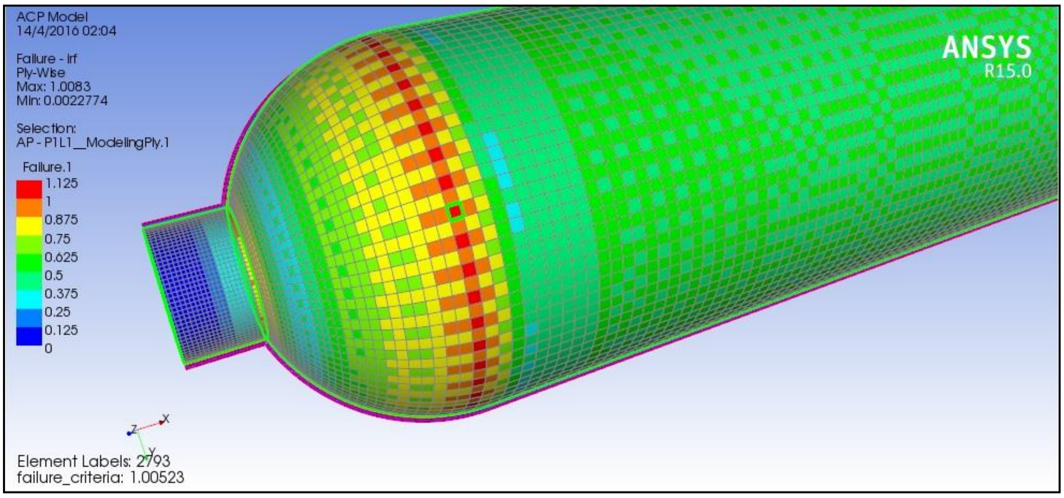

Figure 4.13: Inverse Reverse Factor (IRF) and Failure Point of the Modified Benchmark Model

4.5 Model Parametric Studies

4.5.1 Optimal Filament Orientation Angle Study

As concluded beforehand, in this first parametric study of finding the optimal lamination winding angle, the liner ply is excluded to allow a clearer results comparison between this project and the referred paper. Any inconsistency between the benchmark and project models are to be further investigated.

Therefore, in this parametric study, the model is made up of 6 layers of 0.762 mm thick T300/LY5052 carbon fiber reinforced polymer laminates, which made up a total shell thickness of 4.572 mm. Then, simulation models with lamination angles of 0^o, $\pm15^o$, $\pm25^o$, $\pm35^o$, $\pm45^o$, $\pm55^o$, $\pm65^o$, $\pm75^o$, $\pm90^o$ are iterated using the same approach and failure criteria. The burst pressure results with rounded values are tabulated both in Table 4.2 and Figure 4.14 below. As clearly showed, the concluded optimum lamination angle is $\pm55^o$ [1, 2], where burst pressure is 13.8 MPa.

Table 4.2: Burst Pressure Values from Orientation Angle Study

Lamination Angle	Burst Pressure	First Ply Failure	Ply Material
$\pm0^o$	2.3 MPa	6^{th} Shell Layer	T300/LY5052
$\pm15^o$	2.4 MPa	6^{th} Shell Layer	T300/LY5052
$\pm25^o$	2.8 MPa	6^{th} Shell Layer	T300/LY5052
$\pm35^o$	4.3 MPa	6^{th} Shell Layer	T300/LY5052
$\pm45^o$	9.3 MPa	1^{st} Shell Layer	T300/LY5052
$\pm55^o$	13.8 MPa	1^{st} Shell Layer	T300/LY5052
$\pm65^o$	7.5 MPa	1^{st} Shell Layer	T300/LY5052
$\pm75^o$	5.5 MPa	1^{st} Shell Layer	T300/LY5052
$\pm90^o$	4.8 MPa	1^{st} Shell Layer	T300/LY5052

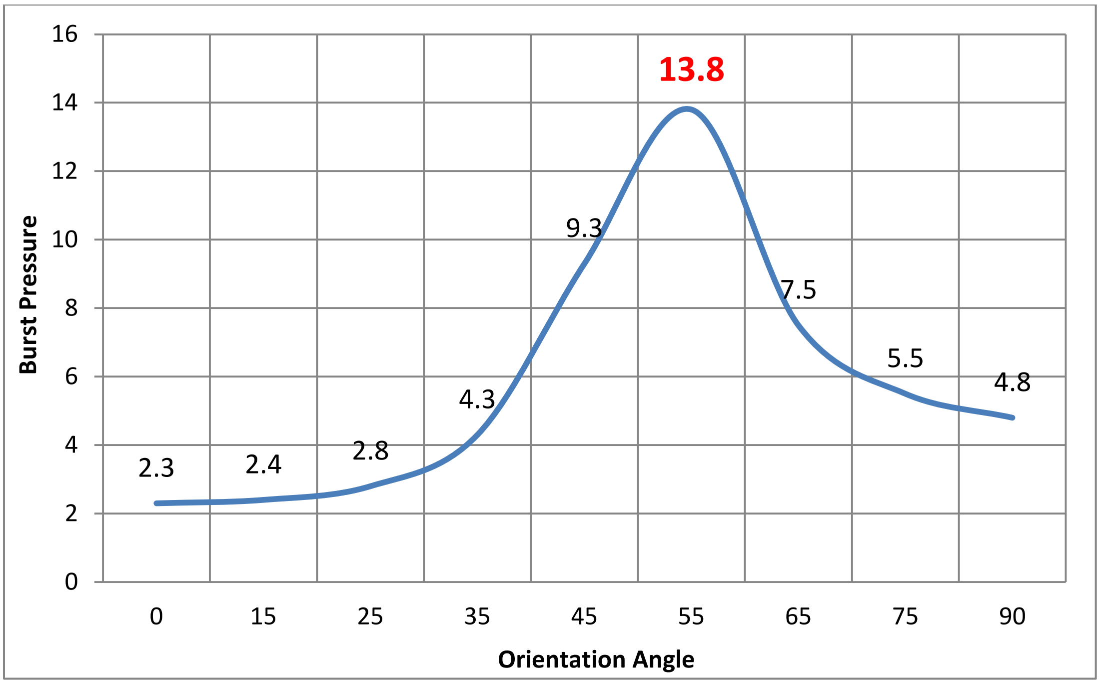

Figure 4.14: Optimal Pressure Vessel Lamination Angle Study

Besides using the simulation approach, the optimal filament winding angle of a composite pressure vessel could be calculated by equating hoop stress equation and axial stress equation of pressure vessel. In order to do so, parameters like pressure, thickness and radius must be equivalent. Theoretically, the acquired value from calculation should be very close to the value obtained from previous simulations of ±55° [1, 2]. Both relations are to be satisfied as below in equations (6 - 9):

$$Hoop\ Stress = nTsin\theta = \frac{Pr}{t} \tag{6}$$

$$Axial\ Stress = nTcos\theta = \frac{Pr}{2t} \tag{7}$$

By dividing the hoop stress over the axial stress, the equation became:

$$tan^2\theta = 2 \tag{8}$$

$$\theta = 54.7^{\circ} \tag{9}$$

As predicted, the optimal laminate orientation angle of ±54.7°, acquired from the calculations above, is very close to the value of ±55° obtained from previous simulation iterations. This validated that the optimal lamination orientation angle is ±55° and this value shall be used in the following studies [1, 2].

4.5.2 Liner Material Type Study

In this parametric study, using the same shell layout with 6 layers of T300/LY5052 carbon fiber reinforced polymer, 3 liners of different materials are to be assigned to find out which type of liner would provide the best strength properties. The studied specimens are metal liners used in Type III pressure vessels as well as non-metal liners used in Type IV pressure vessels. Besides that, a liner-less pressure vessel model is included in this study to compare the difference in pressure vessel burst pressure. The list of liners and their descriptions are shown in Table 4.3 below.

Table 4.3: Types of Liners for Parametric Study

Liner Type	Description	Thickness
Metal	AL 6061 Aluminium Alloy	0.3 mm
Non-Metal	S-Glass	0.3 mm
	High Density Polyethylene (HDPE)	0.3 mm

Using the same failure criteria where the inverse reserve factor (IRF) should be equal to 1.0, it has been found out that the pressure vessel model with the non-metal, high density polyethylene (HDPE) liner could sustain the highest burst pressure of 14.5 MPa, as compared to other models as shown in bar chart in Figure 4.15. Besides that, first ply failure of the HDPE liner pressure vessel happened at the first shell layer rather than the HDPE liner layer as shown below in Table 4.4.

Table 4.4: Burst Failure Values from Liner Type Study

Liner	Burst Pressure	First Ply Failure	Ply Material
HDPE	14.5 MPa	1st Shell Layer	T300/LY5052
No Liner	13.8 MPa	1st Shell Layer	T300/LY5052
S-Glass/Epoxy	8.1 MPa	Liner Layer	AL 6061
AL 6061	6.9 MPa	Liner Layer	S-Glass/Epoxy

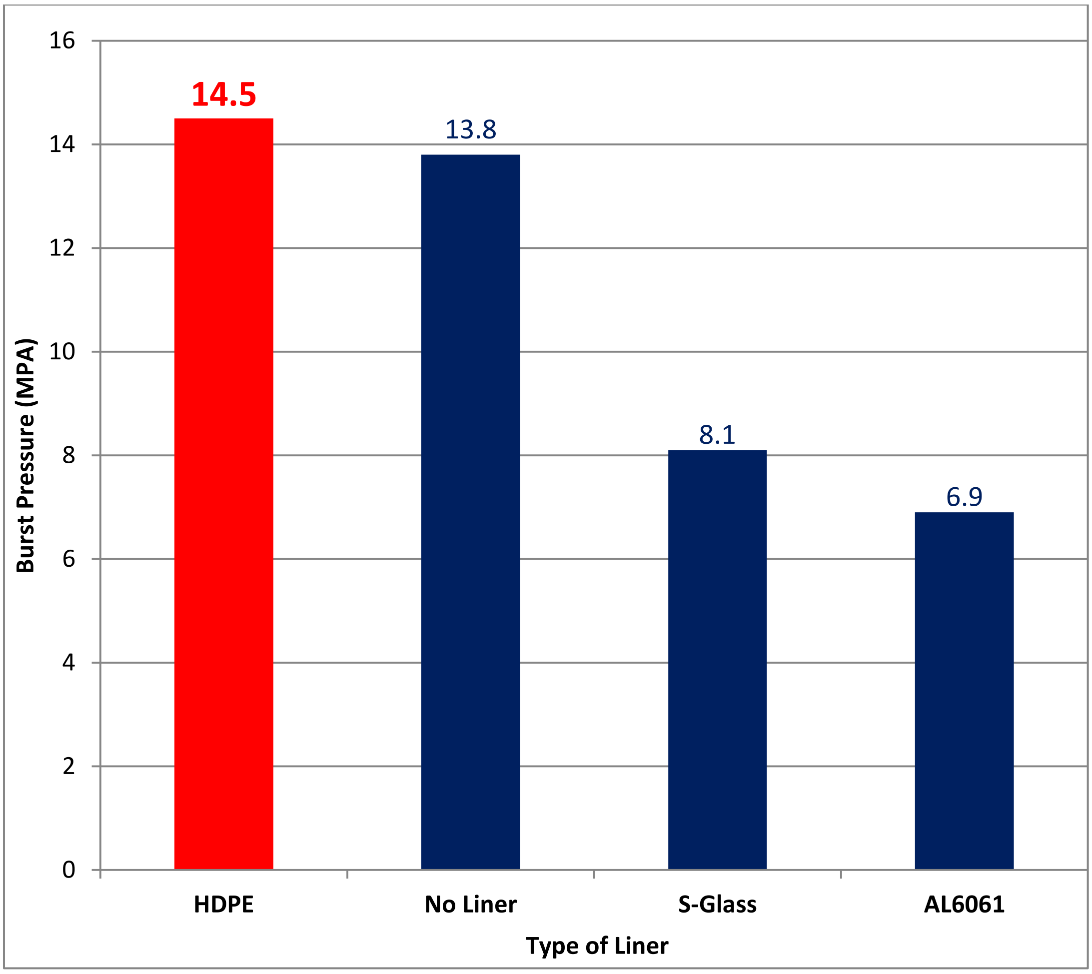

Figure 4.15: Bar Chart of Liner Material Type Study

As mentioned above, the first ply failure of the pressure vessel with HDPE liner occurs at the first shell ply which is made up of T300/LY5052 carbon fiber reinforced polymer rather than the high density polyethylene (HDPE) liner. On the other hand, the other 2 pressure vessel models with glass and metal liners sustained first ply failure at the liner layer rather than at the shell layers.

This concludes that Type IV pressure vessels with non-metal HDPE liners have better strength properties than those Type III pressure vessels due to its thermoplastic liner's material property that could sustain high strain. Normally, high density polyethylene (HDPE) has a yield strain of approximately 11% [30, 31]. However, the polymer could still continue to sustain elongation of more than 1000%, before any breakage happens [30, 31].

4.5.3 Shell Material Type Study

In this case study, different types of shell materials are to be assigned over the HDPE liner that was previously proved to have the best strength properties. Using the same failure criteria and finite element analysis approach, burst failure analysis is then carried out to find out which shell has the best strength properties. The number of shell layers remained as 6 as well as the ply thickness of 0.762 mm.

Besides simulating homogeneous shells where only one material is used to build the pressure vessel shell, a heterogeneous shell is also simulated via mixture of 2 types of shell materials where the layout of this shell as shown in Figure 4.16. In overall, the list of shell layouts involved in this case study are as shown in Table 4.8 below.

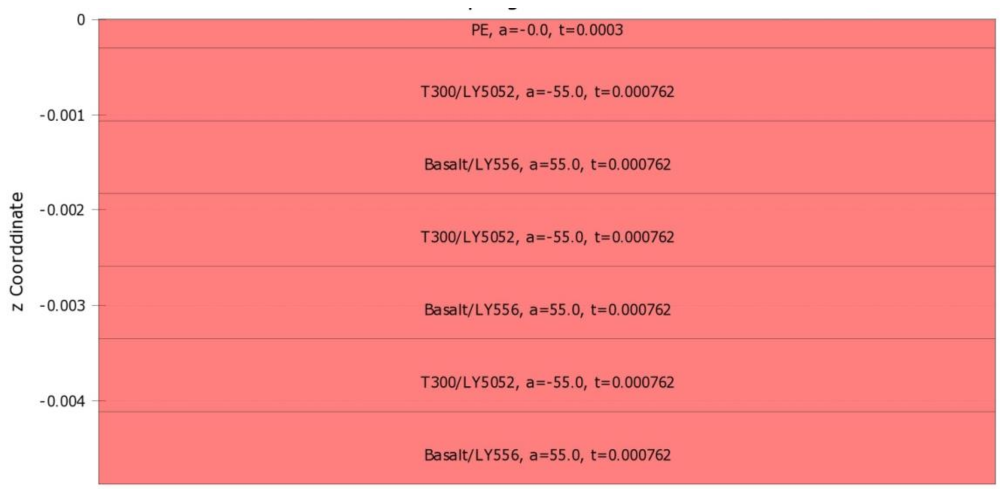

Figure 4.16: Lamination Layout of Composite Pressure Vessel Model with T300-LY5052/Basalt-LY556 Heterogeneous Shell

Table 4.8: Types of Shells for Parametric Study

Type	Description
Homogeneous	T300/LY5052 Carbon Fiber Reinforced Polymer
	Basalt/LY556 Basalt Fiber Reinforced Polymer
Heterogeneous (Mixture)	T300-LY5052/Basalt-LY556 Hybrid

In both Table 4.9 and bar chart in Figure 4.17, it showed that the pressure vessel model with the T300/LY5052 carbon fiber reinforced polymer shell and a high density polyethylene (HDPE) liner could sustain a maximum burst pressure of 14.5 MPa. This study also showed that shell materials with higher stress and strain limits will directly increases the burst strength of the composite pressure vessel. Besides that, a Type IV composite pressure vessel with a homogeneous shell has a higher burst strength as compared to a composite pressure vessel with a heterogeneous shell.

Table 4.9: Burst Failure Values from Shell Type Study

Shell	Burst Pressure	First Ply Failure	Ply Material
T300/LY5052	14.5 MPa	1^{st} Shell Layer	T300/LY5052
T300-LY5052/ Basalt-LY556	8.8 MPa	1^{st} Shell Layer	T300-LY5052/ Basalt-LY556
Basalt/LY556	6.9 MPa	1^{st} Shell Layer	Basalt/LY556

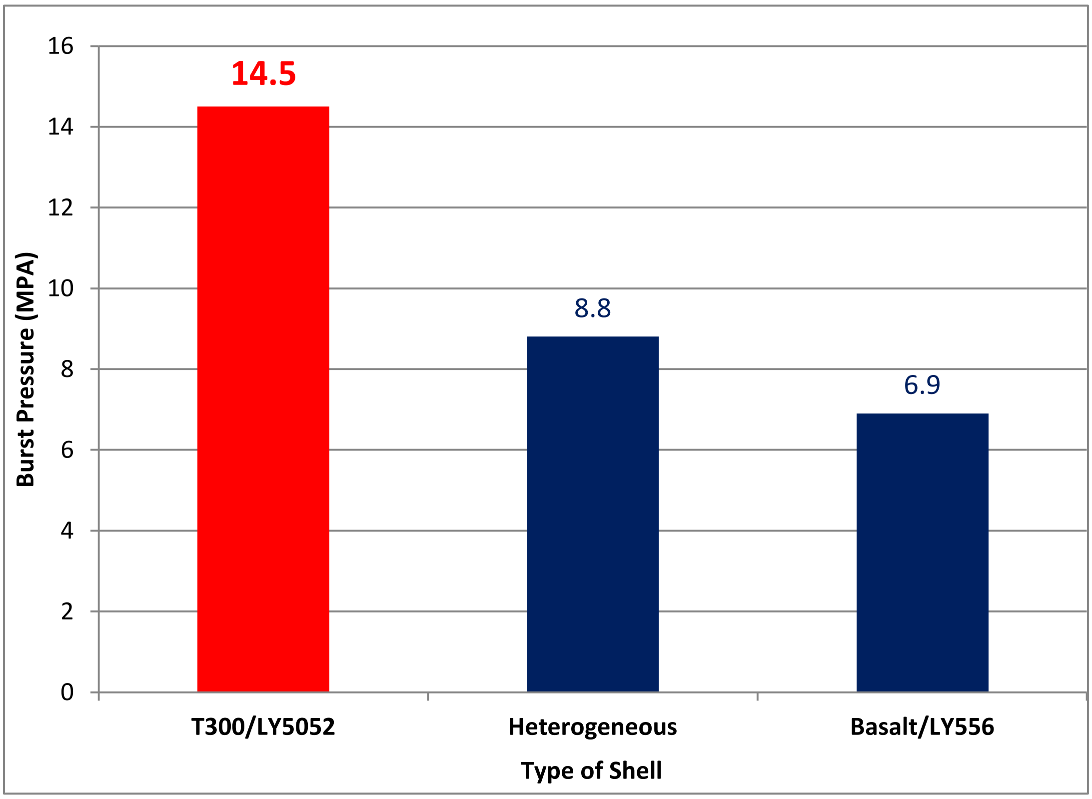

Figure 4.17: Bar Chart of Shell Material Type Study

4.5.4 Strength-to-Weight Ratio Study

In this study, a Type I isotropic pressure vessel was modelled to sustain the equivalent burst pressure of 14.5 MPa as the previously modelled Type IV composite pressure vessel with a high density polyethylene (HDPE) liner and T300/LY5052 carbon fiber reinforced polymer shell. The selected material used to construct this isotropic pressure vessel model is AL 6061 aluminium alloy. As the thickness of the equivalent isotropic pressure vessel is found, weight comparison between both the Type I and Type IV pressure vessels of same strength properties is done.

Using the same failure criteria and simulation approach as all the previous models, the thickness of the isotropic pressure vessel model that could withstand the same burst pressure of 14.5 MPa is found to be 8.1 mm as shown in Figure 4.18. Besides that, the point where failure occurs for the isotropic pressure vessel model is located at the end of the hoop segment as shown in Figure 4.19 below.

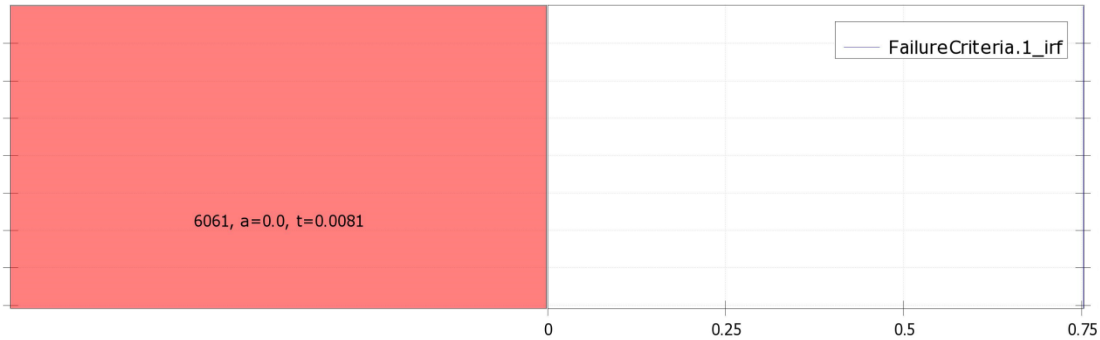

Figure 4.18: Layout of Isotropic AL 6061 Pressure Vessel Model

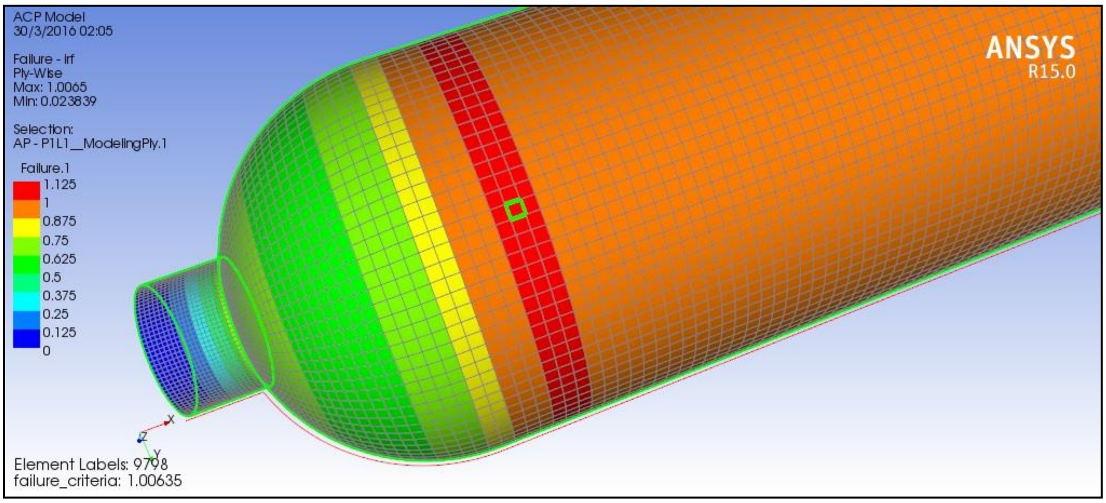

Figure 4.19: Inverse Reverse Factor (IRF) and Failure Point of the Isotropic Model

After the Type I isotropic model of equivalent strength is constructed, the weight values for both of the Type I and Type IV models are found to be 25.2 kg and 8.6 kg respectively, as shown in Figure 4.20 and Figure 4.21 below. Using equation (10) below, the isotropic pressure vessel model (AL 6061) is calculated to be approximately 3 times heavier than the composite pressure vessel model (T300/LY5052). This showed that the composite pressure vessel is lighter to be operated as well as requires 2 to 3 times less in terms of material amount to build a pressure vessel of equivalent strength, thus, showed a better strength-to-weight ratio.

$$Weight\ Ratio = \frac{Weight_{Isotropic}}{Weight_{Composite}} \tag{10}$$

$$Weight\ Ratio = \frac{25.2}{8.6} = 2.97\ \approx 3.0$$

Measures

Weight	25.2066674304
Covered Area	1.15128903095
Modeling Ply Area	1.15128903095
Production Ply Area	1.15128903095
Price	0.0
Center of Gravity	(0.0000,0.0000,-0.0000)

Figure 4.20: Weight of Type I Isotropic Pressure Vessel (AL 6061)

Measures

Weight	8.59211608956
Covered Area	1.15128903095
Modeling Ply Area	1.15128903095
Production Ply Area	1.15128903095
Price	0.0
Center of Gravity	(0.0000,0.0000,-0.0000)

Figure 4.21: Weight of Type IV Composite Pressure Vessel (T300/LY5052)

CHAPTER 5

CONCLUSION

In this project, burst strength analysis on composite pressure vessel was successfully done using finite element analysis and by incorporating failure criteria like Tsai-Wu criterion, Tsai-Hill criterion and maximum stress criterion. Besides that, parametric studies on the optimal lamination orientation angle, liner material type, shell material type and strength-to-weight ratio analysis were successfully carried out.

The results from benchmark model's research paper was validated with slight modifications where the composite pressure vessel was able to withstand a maximum internal pressure of 13.8 MPa at a ply orientation angle of $\pm 55^{o}$ prior to burst failure. Besides that, the optimal lamination winding angle for a composite pressure vessel to sustain maximum burst pressure was proven to be $\pm 55^{o}$ by simulating burst failure of models with various orientation angles as well as via theoretical calculations. [1, 2]. Moreover, at this orientation angle, the point of failure is located at the intersection between the hoop and dome segment of the composite pressure vessel.

In the material based parametric studies, the pressure vessel with a non metallic liner, in this context, a high density polyethylene (HDPE) liner was proven to have better strength properties than other glass and metallic liners like S-Glass/Epoxy glass fiber reinforced polymer and AL 6061 aluminium alloy respectively. The mentioned pressure vessel model with a thermoplastic liner was able to sustain a burst pressure of 14.5 MPa. Meanwhile, the other 3 models with no liner, S-Glass/Epoxy glass fiber reinforced polymer liner and AL 6061 aluminium alloy liner was only able to sustain a lower burst pressure of 13.8 MPa, 8.1 MPa and 6.9 MPa respectively. This has proven that a Type IV composite pressure vessel which has a thermoplastic liner has better strength properties and could sustain a higher internal pressure than a Type III composite pressure vessel. This is because of the high strain properties of high density polyethylene (HDPE) where it could sustain 1000% of elongation before any breakage happens to the materials [30, 31].

On the other hand, this project included a case study to compare burst strength properties of a few types of pressure vessel models with varying shell materials. The case study showed that the T300/LY5052 carbon fiber reinforced polymer shell possessed better strength properties than Basalt/LY556 basalt fiber reinforced polymer shell. The composite pressure vessel with a T300/LY5052 carbon fiber reinforced polymer shell and a thermoplastic liner was able to withstand a maximum internal pressure of 14.5 MPa while the other vessel with a Basalt/LY556 basalt fiber reinforced polymer shell could only sustain a maximum internal pressure of 6.9 MPa. Besides investigating homogeneous pressure vessel shell, both of the aforementioned composite materials were laid in alternating order to form a heterogeneous shell where the hybrid composite pressure vessel had a burst pressure of 8.8 MPa. Thus, it is concluded that composite pressure vessels with a homogeneous shell has better strength properties than those with a heterogeneous shell and able to withstand a higher burst pressure.

The last parametric study was done to compared strength-to-weight ratio between a Type I isotropic pressure vessel and a Type IV composite pressure vessel. The selected material for the construction of the isotropic pressure vessel was AL 6061 aluminium alloy. It was designed to have equivalent strength and internal dimensions of the previously modelled Type IV composite pressure vessel. In overall, the isotropic pressure vessel of equivalent was found to have a thickness 8.1 mm and a weight of 25.2 kg. In contrast, the Type IV composite pressure vessel only had a thickness of 4.872 mm and a weight of 8.6 kg. This showed that the isotropic pressure vessel weighed at least 3 times more than a composite pressure vessel. This led to a conclusion where a Type IV composite pressure vessel has a better strength-to-weight property.

This research project was done with all its objectives met. This project has also provided an insight to future research works on design optimizations of a composite pressure vessel as well as discovering better composite materials for construction of these composite pressure vessels.

CHAPTER 6

FURTHER STUDIES AND RECOMMENDATION

The next phase of this project will be resumed with the following recommendation:

I. Validation of composite pressure vessel burst failure analysis results acquired from finite element analysis using experimental method.
II. Simulation of composite pressure vessel that is made up of composite materials with better strength properties to allow the construction of a stronger composite pressure vessel that could sustain higher burst pressure.
III. The use of last ply failure on the composite pressure vessel model rather than first ply failure to identify ultimate burst pressure. This could be done by utilizing a progressive damage model of the composite pressure vessel.

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