UNIVERSITY OF WINDSOR

Faculty of Engineering

Department of Mechanical, Automotive and Materials Engineering

Stress Analysis (92-311)

Design and Construction of a Pressure Vessel

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Project Team

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Table of Contents

Executive summary

This design report was written to cover the construction of a pressure vessel using nothing, but newspaper, Bristol board, masking tape, and white glue.

Going into this project, the group had to first think about the purposes for this pressure vessel and potential problems that could occur. Then, the students had to conduct their own research on the theoretical aspects of a thin walled pressure vessel to get a basic understanding of its functions and properties. In the following section, the rough drawings done by each team member would demonstrate the thinking process that the team went through in order to create their design. Before these preliminary sketches were put together to create a final design, dimensions of the vessel had to be decided upon by calculating which lengths and thickness would better optimize the amount of stress and internal pressure that the tank could withstand.

After the design and calculation phase, the building of the vessel begins. Before building, different types of materials were gathered to allow the team to play around with different types of thicknesses and rigidness to see what works best in this scenario. When building something, there are always problems that come up which would require design changes or the process used to build the vessel to be changed. After a successful pressure vessel was made, it would be put through various tests to ensure that it will perform at its peak for the contest.

Problem Definition

Problem scope:

The purpose of this project is to design a thin-wall pressure vessel mainly out of Bristol board. The pressure vessel is constrained to specific measurements and criteria, which must be followed throughout the design procedure. With this design, we are expected to record the highest internal pressure that the vessel can withstand, with which the hoop and longitudinal stresses are calculated. By comparing experimental and theoretical average stresses a factor of safety can be determined.

Technical Review:

Thin-wall pressure vessels are widely used across the world, to transport liquids and gases. There are two common types of pressure vessels 1) Spherical pressure vessels, 2) Cylindrical pressure vessels. In this project we are more concerned with cylindrical pressure vessels. An ideal thin-walled pressure vessel is unaffected by bending stresses over most of its cross sectional area. From research and experimentation it is know that cylindrical vessels are less efficient compared to spherical pressure vessels, because: (1) the closed end caps can alter the load distribution around the seams quite significantly (2) also the wall stresses vary with direction (hoop & longitudinal stresses). On a positive note, it is easier to manufacture cylindrical pressure vessels due to its geometrical constraints.

In the analysis of the thin walled pressure vessels, assume the ratio of radius over thickness ($r/t > 10$) to be greater than 10, assume the stress distribution is uniform over the extent of the cylindrical pressure vessel. Additionally, assume that the internal pressure is uniform, and that external atmospheric pressure is negligible, for the simplicity of calculations.

In our analysis of the cylindrical pressure vessel, we first begin by determining the normal stresses in a thin walled circular tank subjected to internal pressure. A stress element with its faces parallel and perpendicular to the surface of the cylinder is shown in fig 1.0. These stress elements correspond to the normal stresses σ1 and σ2, which are known as hoop and longitudinal stresses respectively.

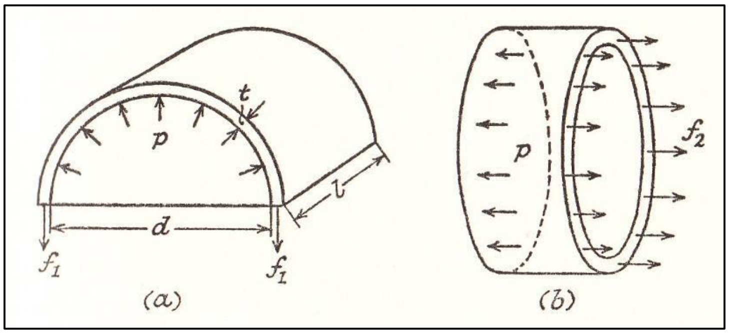

Figure 1: Circumferential and longitudinal stress elements

Circumferential stresses:
The circumferential stresses acting inside a pressure vessel have a resultant equal to
σ1(2bt) (Where b = the length, t = thickness).
Additionally the resultant fore P of the internal pressure is equal to 2pbr (where r = internal radius and p = internal pressure
From the free body diagram, the following equilibrium equation is obtained:

$$\sigma 1(2bt) - 2pbr = 0$$

Hence resulting in the circumferential stress:

$$\boldsymbol{\sigma 1 = \frac{pr}{t}}$$

Longitudinal stress:
The Longitudinal stresses acting inside a pressure vessel have a resultant equal to
σ2(2πrt) (Where r = internal radius, t = thickness).
Additionally the resultant fore P of the internal pressure is equal to $p\pi r^2$ (where r = internal radius and p = internal pressure
From the free body diagram, the following equilibrium equation is obtained:

$$\sigma 2(2\pi rt) - p\pi r^2 = 0$$

Hence resulting in the longitudinal stress:

$$\boldsymbol{\sigma 2 = \frac{pr}{2t}}$$

By comparing both the longitudinal and circumferential stresses it can be seen that:

$$\boldsymbol{\sigma 1 = 2\sigma 2}$$

This means that the longitudinal welded seam must be twice as strong as a circumferential seam.

The above information and more information in reference to theoretical calculations and design considerations can be found in the ASME section 8 division 1 code of the handbook.

Design requirements

The source of the requirements and deliverables listed below are specified by the course outline.

Constraints	Values
Length (mm)	$450 \leq L \leq 500$
Outer Diameter (mm)	$160 \leq L \leq 180$
Thickness (mm)	≤ 4
Mass (g)	$m \leq 600$

Table 1.0: Design Requirements and Constraints

The pressure vessel must be constructed entirely from:

- Bristol board and or Cardboard
- Making tape
- White paper glue
- Cotton or Polyester sewing thread

Design description

Overview:

To construct the pressure vessel, firstly ideation sketches were drawn keeping all the design constraints in mind (see figures 2-6). Using the ideation sketches further detailed and modified drawings were made which gave the project a solid foundation to build upon. Since the project is to design a thin-walled pressure vessel under 600 grams, raw material usage was restricted and compromised for the mass requirements. Initially two methods of construction were established: (1) paper Mache (2) molding Bristol boards. From review papers and technical documents it was common to see that the heads of the pressure vessel were very challenging to make and seal, to avoid leaks and structural deformation. One of the approaches to tackle such a situation was to use paper Mache, where pieces of paper are glued onto a balloon which acts a mold for the vessel heads, and these heads are in turn paper Mache onto the cylinder, which is made from gluing rolls of paper onto one another. Secondly, to make hemi-spherical heads which is not plausible from a planar sheet of paper was challenging, this challenge lead the design to use a mold made from wood that was processed through a CAD-CAM process. This mold was used to shape the hemispherical heads, a total of 3 pieces are glued including the cylinder and two of the heads. To ensure no leaks, glue and masking tape were later applied onto the spherical heads. To ensure absolute dryness in the glue, a twenty four hour curing time was also allotted. This technique resulted in great results, hardening the structure and achieving the required stiffness of the materials.

Preliminary Sketches:

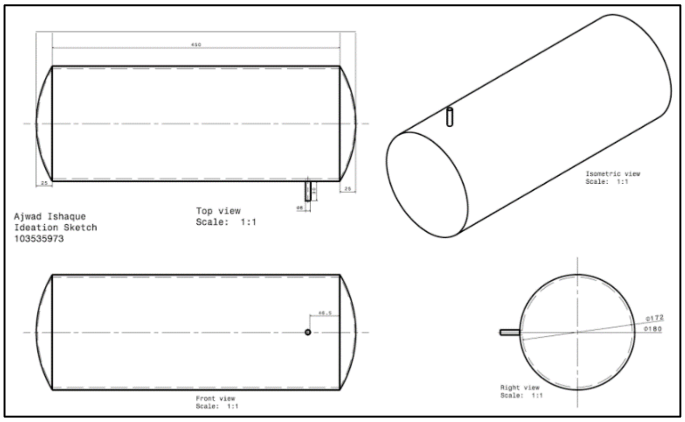

Figure 2: Ajwad Ishaque

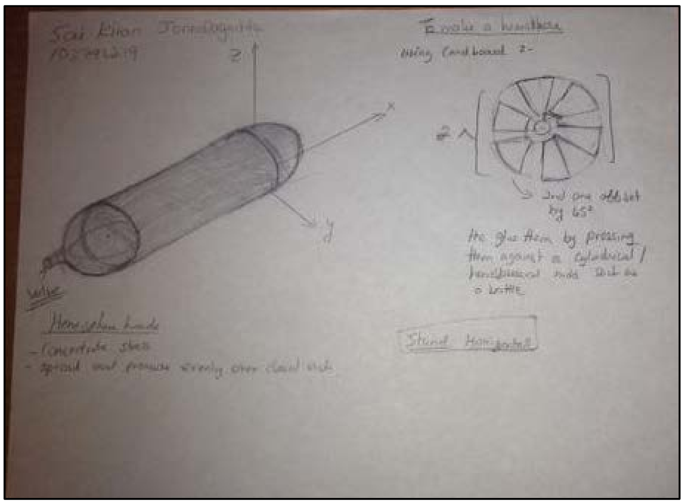

Figure 4: Sai Kiran, Jonnalagadda

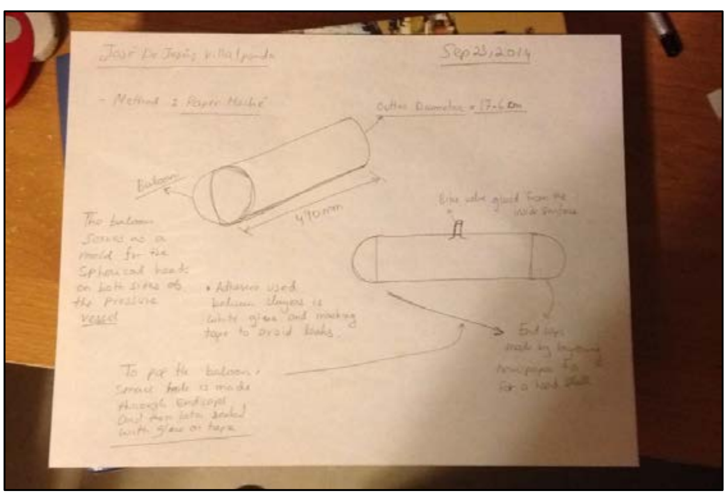

Figure 6: Jose De Jesus Villalpando

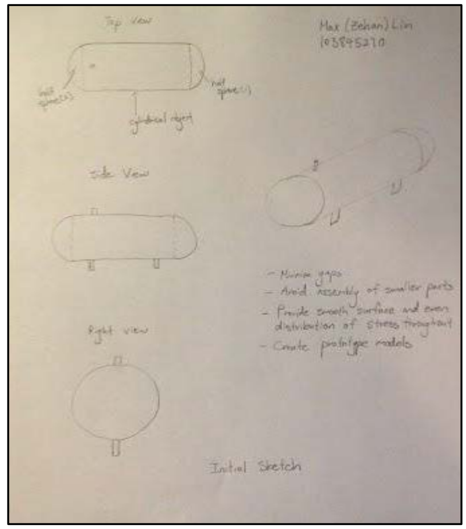

Figure 3: Max (Zehan) Lin

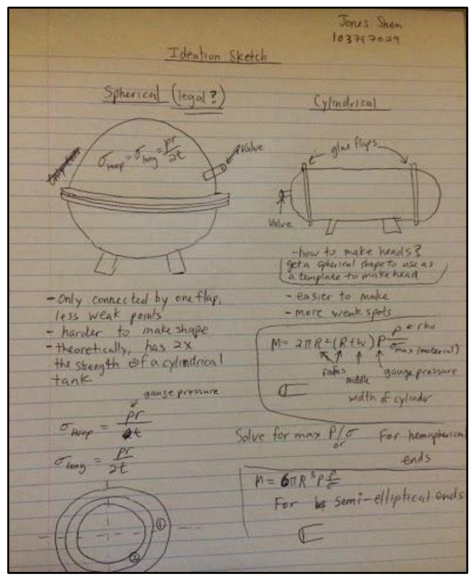

Figure 5: Jones Shen

List of Components

Final Design:

Item	Specification	Qty	Cost	Total Cost
Bristol Board	Poster Board, 22" x 28"	5	$0.50	$2.50
Masking Tape	Masking Tape 24Mm X 55M	3	$3.29	$9.87
White Glue	3L	1	$27.79	$27.79
Bike Tire Tube	Supercycle AV Standard Bike Tube, 26 x 1-3/8-in	1	$5.99	$5.99
Newspaper	From recycle bin	3	$0.00	$0.00
		11		**$46.15**

Table 1.1: Raw materials used for construction

Usable Total Material Cost:

Item	Specification	Qty	Cost	Total Cost
Bristol Board	Poster Board, 22" x 28"	50	$0.50	$25.00
Masking Tape	Masking Tape 24Mm X 55M	5	$3.29	$16.45
White Glue	3L	1	$27.79	$27.79
While Glue	400 ml	1	$2.99	$2.99
Bike Tire Tube	Supercycle AV Standard Bike Tube, 26 x 1-3/8-in	5	$5.99	$29.95
Newspaper	From recycle bin/bought	10	$1.00	$1.00
Mold (for heads)	4.5 cm depth x 18 cm diameter	1	$18.00	$18.00
		73		**$121.18**

Table 1.2: Usable Total Material Costs

Voided Material Cost:

The following materials were either initially bought to aid in the construction of various parts such as the end caps, molding, clamping or were under the impression that they could be used as components to the final design.

Item	Specification	Qty	Cost	Total Cost
Craft Paper Roll	1/64 in x 35 in x 140 ft	1	$12.98	$12.98
Cardboard	Durable 1mm thick	1	$0.99	$0.99
Styrofoam bowl	Semicircle – 8” with 1 “ radius	1	14.00	14.00
Styrofoam ball	6”	1	14.00	14.00
		4		**$41.97**

Table 1.3: Voided material costs

Final Design

Although the following illustration depicts a pressure vessel that is made entirely out of Bristol board, it is not. Bristol board was only used as the barebones for which newspaper and paper mache techniques could be applied. However, dimensions listed were maintained to the best of their ability. The bare-bone had a thickness of **1mm** and the overall thickness was **3.79mm.**

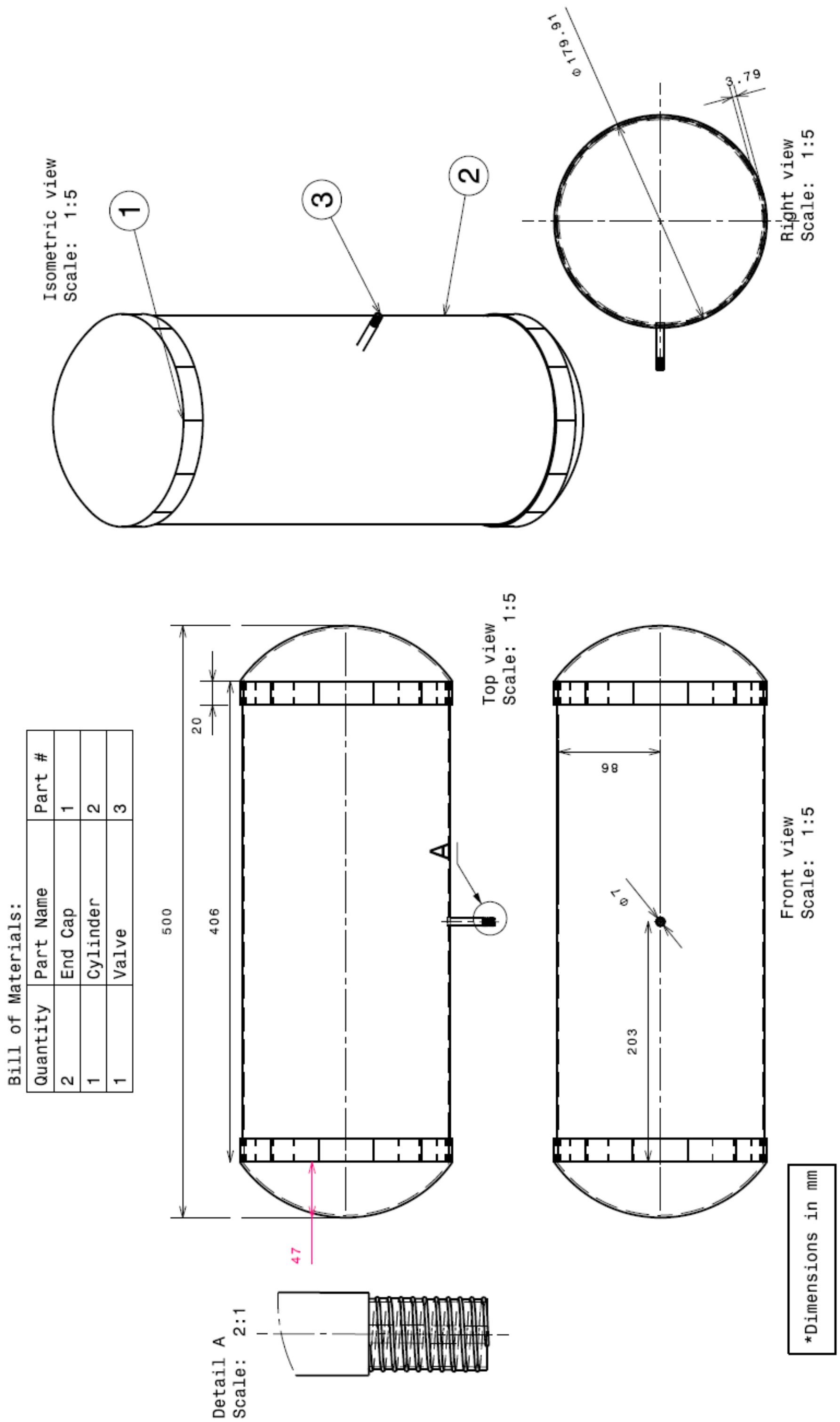

Figure 7: Illustrates the drafting of the final design using CATIA. Note all dimensions are in mm and the thickness (as stated in the right view) is 3.79mm to leave space for masking tape/glue.

Final Result:

Figure 8: Final Design Result

Testing and Evaluation

$$V_{pv} = V_{cyl} + 2V_{cap} = \pi r^2 h + 2\left(\frac{\frac{4}{3}\pi r^2 h}{2}\right) = \pi(88)^2(41) + \frac{4}{3}\pi(88)^2(45)$$

V_{pv} = 10439322.4 mm^3 = 0.01044 m^3 ≈ 10.4477 liters

Calculations:

Since the general shape of the pressure vessel consists of a cylinder and two hemispheres, the following equation can be used to calculate an estimate for the maximum pressure that the tank can hold:

$$\sigma_{hoop} = \frac{pR}{t}$$

Where:

- R = the inner radius of the cylinder
- p = the internal pressure relative to gauge pressure
- t = the thickness of the cylinder wall
- σ = the yield stress that the material can operate

Givens:

- σ = 2.5MPa (Assumption based off of properties of coated paper, also taking into account of the glue and tape)
- t = 4mm
- R = 90mm – 4mm = 86mm

$$p = \frac{\sigma_{hoop} t}{R} = \frac{(2.5)(4)}{(86)} = 116.3\ kPa = 16.8\ psi$$

Finite Element Analysis:

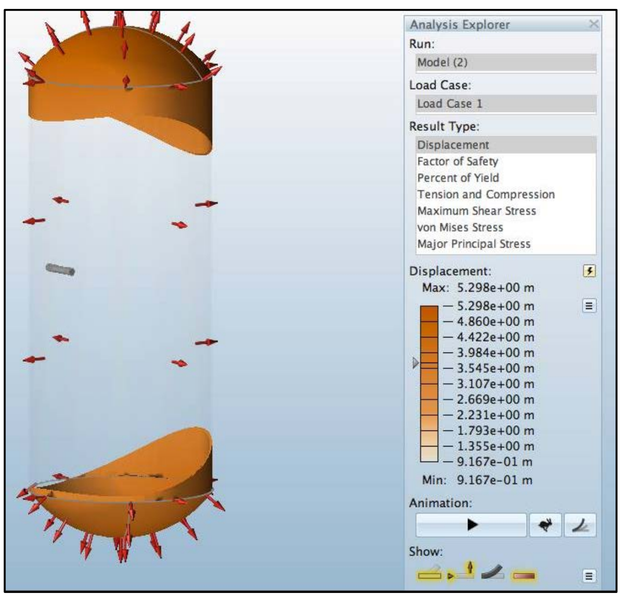

Image 1.0: Illustrated in orange is the max and min displacements that is yielded by the end caps before it ruptures, which also states that the end caps are the first ones to rupture or detach from the pressure vessel.

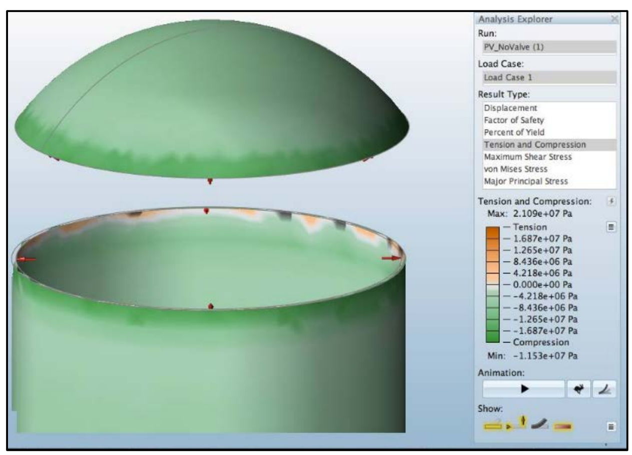

Image 1.1: Illustrates the tension and compression at the joint of the end cap and cylindrical body. The areas colored in brown represent tension whereas green represents compression. From this illustration it is safe to conclude that majority of the pressure vessel will experience a compressive behavior.

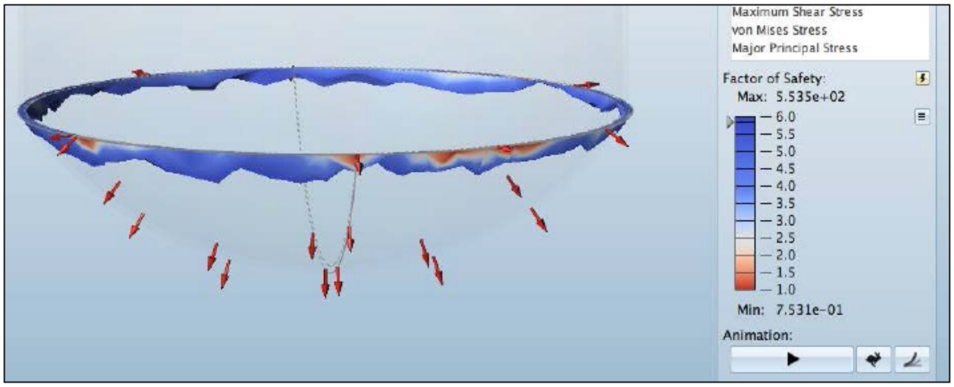

Image 1.2: Demonstrates critical points on the joints between the end caps and cylinder, this is represented by the red areas. The figure documents minimum and maximum factor of safety values which are between 1 and 5.

<u>Theoretical Results in accordance to sample calculations and approximations</u>

Stress (MPa)	Pressure (psi)
0.00	0.00
0.90	6.07
1.10	7.42
1.30	8.77
1.50	10.12
1.70	11.47
1.90	12.82
2.10	14.17
2.30	15.52
2.50	16.86

t	4
r	86
Conversion factor kPa-Psi	0.145038

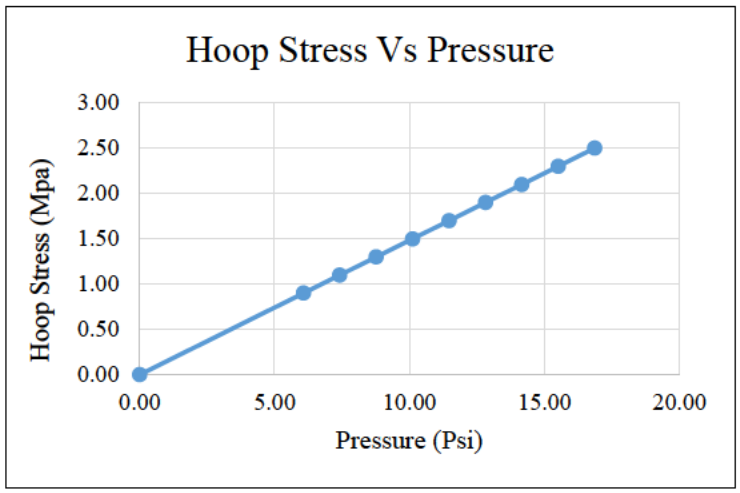

Figure 9: Illustrates theoretical hoop stress (MPa) vs. internal pressure (psi)

<u>Experimental Results in accordance to sample calculations and approximations</u>

Experimental	
Stress (MPa)	**Pressure (psi)**
0.00	0
0.37	2.5
0.89	6
0.96	6.5
1.10	7.4
1.14	7.7
1.08	7.3
1.19	8

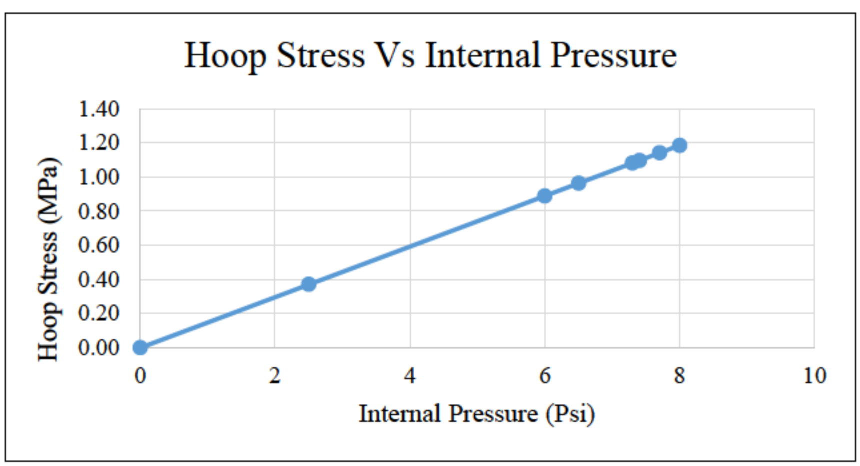

Figure 10: Illustrates experimental hoop stress (MPa) vs. internal pressure (psi)

Failure Analysis and Discussion

The main challenge in this project was to design an efficient way to fasten the end caps onto the cylinder. However, the cylindrical body, for the most part, was relatively easy to make. A total of four methods were used to fasten the end caps onto the cylinder, primarily to avoid leaks and seal the entire vessel.

After conceptualizing the method of making a pressure vessel, the team put together the first design which brought with it several learning outcomes. The first of which was the fact that putting together something needed to be done in a way that required patience. Every gluing technique had its own application (see failure and discussion) and time limit. A mold was constructed in order to aid in the construction of the semicircular heads (*see Figure 9: Appendix C*).

The first prototype was made from a combination of Bristol board and newspaper, resulting in a significant increase in mass (*see Appendix A*). In addition, it did not contain any air, primarily because the glue was still wet and was diluted with water when applied. Not only did this increase the time required for the glue to dry, but it also made its shearing capabilities to decrease. Tests were conducted to find these air pockets by wrapping a plastic bag over each head and pumping in air using a bike pump. If the bag was inflated, it was certain that there were leaks, which was very noticeable. Another method we used to test leaks was inspired by how children blow bubbles of air. Dish washing soap was added to the head and air was again pumped. This time however, bubbles originated from the pocket holes from where the air leaked. Even though patches were made and excessive masking tape was applied, avoiding leaks was inevitable.

A suggestion was made by a group member that the pumps that were being used (bike pumps) were not supplying enough air to sustain any pressure in the pressure vessel. It appeared that the air leaked at the same rate as one stroke of the bike pump was made. Hence the group decided to go to a gas station where they could use the compressed air machine to ensure that the tank was leaking and not the bike pump, but in the end, the pressure vessel was the issue.

The second design, by the material and method used, did show a little more promise as a method of paper Mache and use of balloons to shape the end caps was applied. This time, however, the glue was given proper time to dry. Visual inspections every 30-40 minutes were made before a desired layer of newspaper was added to the end caps. (See *Appendix B for figures)*

The pressure vessel was tested with a bike pump and managed to sustain 4.5 psi of air before it presumably leaked from the valve area. The team believed that the valve on the vessel got pushed in by the bike pump was made to the pressure vessel valve and as a result, deformed the tape inside which was holding it in place (*see Figure #: 3 - Appendix A*)

For the third design, the team decided to try a more flexible and lightweight material (no-glosss). This led to the caps being made out of the wooden mold that was previously mentioned. At first a pin-wheel type template (*see Figure #: 7 – Appendix C*) was used to mold the end caps resulting in extremely small holes and cracks, but by the time this issue was found, the end caps were already glued and taped onto the cylinder which rendered the entire cylinder useless. Later on, the templates for the end caps were modified by covering more area and minimizing the spaces between each wedge (*see Figure #: 8 – Appendix C*) ,three bristol board templates were glued together with an extra layer of glue between each layer to seal up any possible cracks or crevices. To speed up the process of drying and at the same time to maintain the flexibility of the torispherical shape the mold was kept near a heating device. Once the end caps were complete, joining the end caps to the cylinder required analyzing the geometric configuration of both the cylinder and end caps, since the mold was set to a depth of 4.5 cm, geometrically it is not possible to create a spherical shape where the depth is not equal to the radius of the sphere. Since the ends of the end caps were not in collinearity with the cylindrical end, it became very troublesome to figure out a solution to attach the two together.

After going through an extensive redesigning process, the issue was resolved by making small incisions from the ends of the end caps to the next immediate surface of the female end of the mold (*see Figures #: 11 & 12 – Appendix C*). Once the cuts had been made, the folded ends of the end caps were glued onto the cylinder creating a uniform seam that was reinforced with layers of glue for extra strength and firmness. In this process, fastening one of the end caps to the cylinder was relatively easy, as the mold used to make the cylinder provided structural firmness during the gluing process. On the other hand, gluing the other end cap to the other side required a hard surface to prevent the cylinder from deforming or collapsing on itself. To solve this issue, the use of a gasket like structure made from two strips of Bristol board was fabricated and the second end cap was glued, which completed the entire pressure vessel.

Overall, this project allowed the group to explore, in depth, the potential of using Bristol board and paper mache. Instead of using easier techniques such as grinding newspaper and mixing it with glue (similar to cement), the team in general chose to adjust their initial designs. This was because the paper mache type structure, when deformed, would cause a brittle type of reaction resulting in challenging repairs. Furthermore, it was concluded that in order to use white glue properly, not only does proper time have to be given, but application has to be uniform on the surfaces of the material. Diluting the glue with water results in weaker bonds and requires more time to dry.

Conclusion

After going through with this design project of building a pressure vessel, it was found that using just newspaper and Bristol board, it can theoretically hold 16.8psi whereas in real life, after being tested, it can approximately hold around 16psi. The biggest lesson that the team learned was that as the radius of the cylinder in the pressure vessel decreased, the internal pressure will increase. The FEA that was done was based off of a plastic material as there was no material choice for cardboard/bristol board in the simulation software. The results obtained are the closest approximation to the final design.

References

1. http://www.paperonweb.com/paperpro.htm#Strength%20Properties
2. http://www.tiniusolsen.com/resource-center/mpa-psi.html
3. http://web.mit.edu/course/3/3.11/www/modules/pv.pdf