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Design and Analysis of Polymer Matrix Composite Pressure Vessel

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ABSTRACT

Filament-wound composite pressure vessels are an important type of high-pressure container that is widely used in the commercial and aerospace industries. The metallic pressure vessels are having more strength but due to their high weight to strength ratio and corrosive properties they are least preferred in aerospace as well as oil and gas industries. These industries are in need of pressure vessels which will have low weight to strength ratio without affecting the strength. On the other hand PM composite materials with their higher specific strength and moduli and tailorability characteristics will result in reduction of weight of the structure.

In this dissertation work ANSYS software is used to carry out the structural analysis of PM composite pressure vessels. Attempts have been made in this work not only to explore the potential utilization of carbon fiber but also a means of mixing of glass fiber in the polymer composites for making value added products.

The hybrid composites (glass and carbon fiber with four layers) have been prepared by hand layup technique to test their strength under different condition and various mechanical tests like tensile, impact, flexural and hardness will be conducted.

For the same geometrical parameters of the steel pressure vessel FE Analysis of PM composite pressure vessel is to be carried out and stresses for different internal pressures are determined. The design is to be carried out in design software solid works and to be analyzed in ANSYS workbench. Then the results of steel pressure vessel and composite pressure vessel are to be compared for stress results

I. INTRODUCTION

E. 0. Bergman[1] states that the internal pressure applied to pressure vessels head and body to produce axial loading and stress results of the vessel. These result in axial tensions and compressions in the shell, which must be combined with the effects of the pressure loading to give the total longitudinal stress acting in the shell. The design method to be used depends on whether the longitudinal stress in the shell is tension or compression, and on whether the vessel is subjected to internal or external pressure.

Shafique M.A. Khan[2] concludes that the highly stressed area, beside the pressure vessel at the saddle horn, is the flange plate of the saddle. The maximum load on a saddle may be conservative or liberal, depending upon the value of the ratio A/L used. (Fig. 1) Furthermore, the design of the saddle structure may be optimized by redesigning selectively.

A value of 0.25 for the ratio A/L is favored for minimum stresses in the pressure vessel and the saddle. The physical reason for favoring an A/L close to 0.25 may lie in the fact that at this ratio, each saddle is located roughly at the center of the half of the pressure vessel thus supporting the pressure vessel or alternatively loading the saddle uniformly. The slenderness ratio (L/R) of less than 16 is found to generate minimum stresses in the pressure vessel and the saddle.

Design procedures for pressure vessel by H. Mayer, H.L. Stark, S. Ambrose[3] concludes that practical difficulties arise for the designer in the fatigue analysis of welds in pressure vessels. For example, the geometry of weld toes are effectively singularities for the purpose of elastic finite element stress analysis. Used national standards, such as ASME require elastically derived peak stress intensity at the highly localized peak stress location. Other standards such as BS5500 allow categorization of the weld detail, but rely on the range of maximum principal stress without apparently taking account of multiaxial stresses. When calculating the fatigue life of some components the two code differed by a factor on life of greater than 10. The major design stress parameters are the stress intensity range and the principal stress range were evaluated for their performance over the scope of fatigue conditions they were required to predict and their ability to calculate. It was concluded that a practical and conservative fatigue analysis approach for a given weld detail is to use for the stress parameter the larger of stress intensity range and principal stress range, and to avoid the difficulty with the singularity at the weld toe by extrapolating from the surrounding values to give geometric stress at the singularity.

Alexey I. Borovkov and Dmitriy S. Mikhaluk[4] describe the results of 3D structural contact FE analysis of high-pressure vessel (HPV). The research is carried out to analyze stress concentration zones and to determine variables for design optimization. The sub modeling method is used to analyze zones with complex geometry. Experimental strain measurements are used to verify the 3D model and the obtained results. The comparison of experimental results and FE modeling is presented. The description of methods and results of multi-parameter design optimization are presented. Such important results of optimization as the decrease of steel intensity and outline size of the HPV are obtained. The multiplier of HPV is used for the external pressure increase and transfer to the working sell. Various material models are used to describe multiplier parts.

The results of multiplier 3D structural contact analysis are presented. The importance of the results obtained and good correlation with experiments make it possible to carry out similar analyses for various HPV that are widely used in industry.

David Heckman[5] tested three dimensional, symmetric and axisymmetric models; the preliminary conclusion is that finite element analysis is an extremely powerful tool when employed correctly. Depending on the desired solutions, there are different methods that offers faster run times and less error. The two recommended methods included symmetric models using shell elements and axisymmetric models using solid elements. Contact elements were tested to determine their usefulness in modeling the interaction between pressure vessel cylinder walls and end caps.

Levend Parnas and Nuran Katircl, [6] analytical procedure is developed to design and predict the behavior of fiber-reinforced composite pressure vessels under combined mechanical and hydrothermal loading. The cylindrical pressure vessel is analyzed using two approaches, which are thin wall and thick wall solutions. It is shown that for composite pressure vessels with a ratio of outer to inner radius, up to 1.1, two approaches give similar results in terms of the optimum winding angle, the burst pressure, etc. As the ratio increases, the thick wall analysis is required.

Jaroslav Mackerle[7] gives finite element methods (FEMs) applied for the analysis of pressure vessel structures/components and piping from the theoretical as well as practical. He classified his reference papers in these categories: linear and nonlinear, static and dynamic, stress and deflection analyses; stability problems; thermal problems; fracture mechanics problems; contact problems; fluid–structure interaction problems; manufacturing of pipes and tubes; welded pipes and pressure vessel components; development of special finite elements for pressure vessels and pipes; finite element software; and other topics. Among the numerical procedures, finite element methods are the most frequently used.

COMPOSITES FOR PRESSURE VESSEL

Fibre-reinforced plastic (FRP) (also fibre-reinforced polymer) is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually glass, carbon, aramid, or basalt. Rarely, other fibres such as paper or wood or asbestos have been used. The polymer is usually an epoxy, vinylester or polyester thermosetting plastic; and phenol formaldehyde resins are still in use. FRPs are commonly used in the aerospace-, automotive-, marine- and construction industries; and in ballistic armor.

A polymer is generally manufactured by step-growth polymerization or addition polymerization. When combined with various agents to enhance or in any way alter the material properties of polymers the result is referred to as a plastic. Composite plastics refer to those types of plastics that result from bonding two or more homogeneous materials with different material properties to derive a final product with certain desired material and mechanical properties. Fibre-reinforced plastics are a category of composite plastics that specifically use fibre materials to mechanically enhance the strength and elasticity of plastics. The original plastic material without fibre reinforcement is known as the matrix. The matrix is a tough but relatively weak plastic that is reinforced by stronger stiffer reinforcing filaments or fibres. The extent that strength and elasticity are enhanced in a fibre-reinforced plastic depends on the mechanical properties of both the fibre and matrix, their volume relative to one another, and the fibre length and orientation within the matrix. Reinforcement of the matrix occurs by definition when the FRP material exhibits increased strength or elasticity relative to the strength and elasticity of the matrix alone.

MATERIALS USED

Various materials being used in the fabrication process are as follows

- Epoxy resin (LY556)
- Glass fiber
- Sisal fiber
- Pine apple fiber
- Carbon fiber
- Mica sheet

LAMINATES PREPARATION PROCEDURE

FIBER SIZING

A.The woven roving of glass and carbon fiber and chopped strand mat of glass fiber were marked with a marker pen for size of 300mm * 300mm.

B.The fibers are cut to above mentioned dimensions. A special cutting scissors was used as fibers is an abrasion resistant fiber.

C.For carbon fiber laminate 2 layers of carbon and a layer of glass fiber were taken.

D.For glass and sisal fiber laminate 2 layers of glass fiber and 300 gram of sisal fiber was taken.

E.For glass fiber,sisal ,pine apple fiber laminates 2layers of glass and mixing of sisal and pina fiber were taken.

F.The number of fiber layers is chosen such that the total thickness of laminate reaches a min. of 3mm.

RESIN AND HARDENER QUANTITIES

A.For glass fiber and carbon fiber the quantity of resin was taken in the ratio 1:1 as both the fibers where of woven roving type i.e., 1g resin for 1g fiber.

B.For E glass fiber the quantity of resin to fiber was in the ratio 2:1 as the resin was of chopped mat strand. Hence 2g resin for every 1g fiber.

C.10% extra resin was added along with above quantity to aid for wastage. Wastage occurs because of deposition of resin on the sides of the mug and on the hand brush.

D.After adding extra resin the total amount of it is obtained. Now, 10% of hardener with respect to the resin's amount is added and stirred thoroughly. Hence for every gram of resin 0.1g of hardener is added.

E.For glass-carbon fiber laminate, the weight of 2layers of carbon and 1 layer of glass. Hence the resin quantity 250g.

F.For glass-sisal laminate, the weight of 3layers of fiber was 112g. Therefore, the resin quantity is 750 gram

G.For glass - sisal-pina, the weight of 3layers 300 gram . consequently, the resin amount 700gram.

LAMINATE MAKING

A.The laminate preparation is started as soon as the resin and hardener are mixed as the curing process gets started.

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B.A thin plastic sheet of 400mm * 400mm is placed on a clean and flat wooden surface.
C.Now the resin-hardener mixture is applied on the plastic film and spread properly on all sides using hand roller.
D.Now the base fiber is placed on the resin, after which resin is poured on the fiber layer and using hand brush it is spread all over the fiber layer equally.
E.The same process is repeated for all the fiber layers and after applying final layer of resin the laminate is covered with a plastic film.

HAND LAY-UP PROCESS

Resin is mixed with a catalyst or hardener if working with epoxy, otherwise it will not cure (harden) for days/ weeks. Next, the mold is wetted out with the mixture. The sheets of fibers are placed over the mold and rolled down into the mold using steel rollers. The material must be securely attached to the mold, air must not be trapped in between the fibers and the mold. Additional resin is applied and possibly additional sheets of fibers. Rollers are used to make sure the resin is between all the layers, the fiber is wetted throughout the entire thickness of the laminate, and any air pockets are removed. The work must be done quickly enough to complete the job before the resin starts to cure. Various curing times can be achieved by altering the amount of catalyst employed.

TESTING

Tensile testing

Tensile testing machine

Specification of the Machine

Capacity : 5 000 Kg's

Resolution : 0.1 Kg's

Load Indicator : Electronic load cell

Displacement : 600m.m by digital encoder

Software : auto instruments

The machine will create the curve while the testing is running.

Table Tensile test results table for Glass and Carbon filler

Width(mm)	Thickness(mm)	Break load (KN)	Tensile strength N/mm²	Tensile modulus kN/mm²
12	3.3	7.908	199.70	30.15
12	3.3	15.740	396.56	60.08
12	3.3	8.898	224.70	25.366
11.5	3.3	6.911	182.13	20.561

Table Tensile test results table for Glass – sisal fiber

Width(mm)	Thickness(mm)	Break load (KN)	Tensile strength N/mm²	Tensile modulus kN/mm²
12	3.3	7.908	199.70	22.544
2.2	3.3	1.611	221.91	25.051
12	3.3	8.898	224.70	25.366
11.5	3.3	6.911	182.13	20.561

Flexural

Flexural testing equipment

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Table Flexural test results table for glass and carbon fiber

Width (mm)	Thickness (mm)	Break load (KN)	Flexural strength(N/mm²)
12.375	3.1	3.450	2.523
12.53	3.1	3.60	2.601
12.38	3.1	3.650	2.670

Table Flexural test results table for Glass – sisal fiber

Width (mm)	Thickness (mm)	Break load (N)	Flexural strength(KN/mm²)
15.7	3.1	145.322	109.024
16.2	3.05	166.079	141.711
15.45	3.2	122.927	132.228

Sample tested in a flexural machine

Impact test (Charpy)

Charpy testing apparatus

Table Impact test results table for glass and carbon fiber

Width (mm)	Thickness (mm)	Energy (joules)
12.37	3.2	7.4
11.85	3.1	8.6
12.85	3.1	9.2

Table Impact test results table for Glass – sisal fiber

Width (mm)	Thickness (mm)	Energy (joules)
12.37	3.2	4.5
11.85	3.1	3.2
12.85	3.1	6.4

Rockwell hardness test

A Rockwell 574 Series Hardness Testers

Table Rockwell hardness test results table for glass-carbon fiber

Sample Id	Location1	Location2	Location3
1	94.5HRL	99.5 HRL	93.0 HRL
2	87.9 HRL	88.1 HRL	90.6 HRLL

Table Rockwell hardness test results table for Glass – sisal fiber

Sample Id	Location1	Location2	Location3
1	95.4HRL	98.9 HRL	110.2HRL
2	97.9 HRL	86.1 HRL	93.6 HRLL

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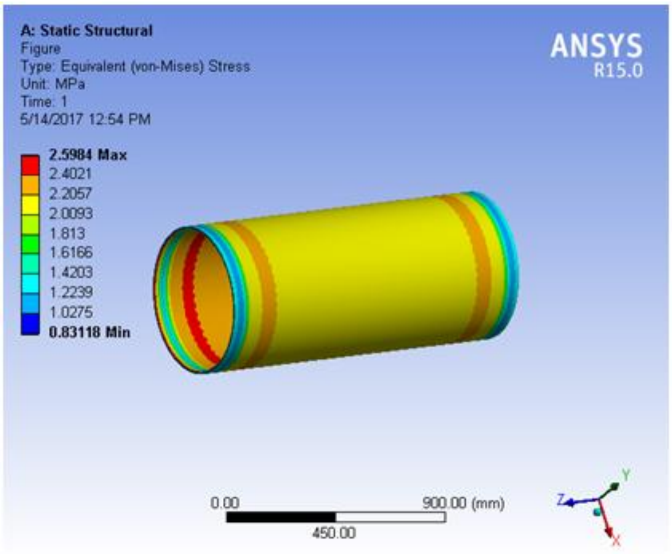
Water absorption test

Water absorption is used to determine the amount of water absorbed under specified conditions. Factors affecting water absorption include: type of plastic, additives used, temperature and length of exposure. The data sheds light on the performance of materials in humid.

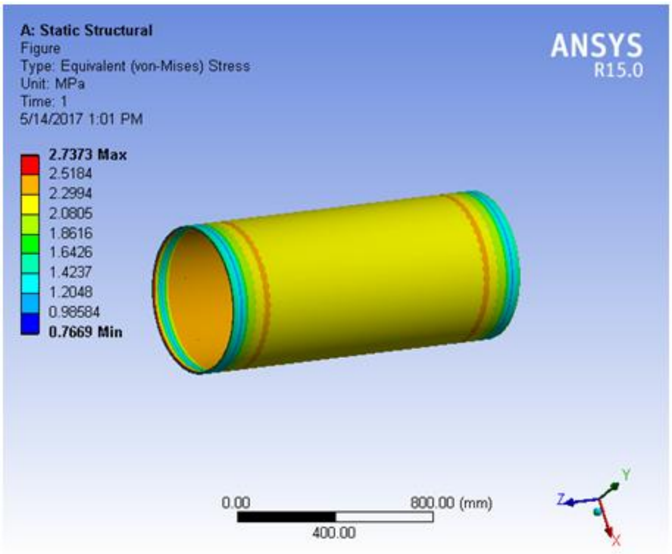
Fig. : Weighing machine

Fig. : Water absorption test

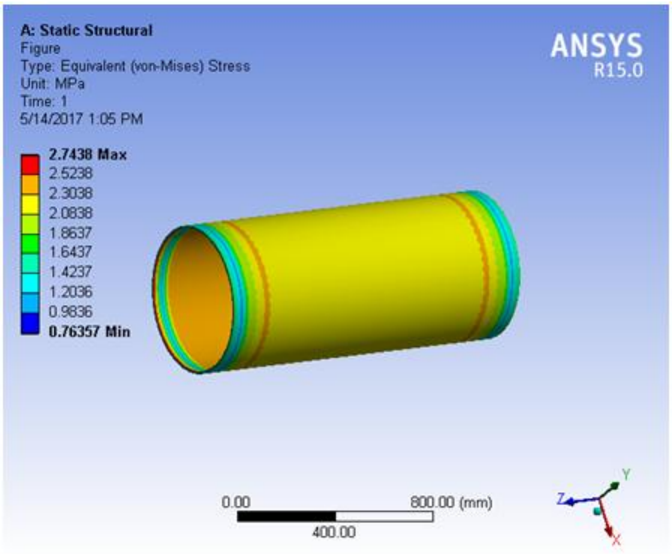
ANALYSIS USING ANSYS



VON MISES FOR MILD STEEL



VON-MISES FOR GLASS AND CARBON FIBER



VON-MISES FOR GLASS -SISAL FIBER

Comparison of results

Properties materials	Tensile Strength N/mm^2	Flexural Strength KN/mm	Impact Strength Joules	Hardness HRC	EI values $MNmm^2$	Poisons ratio	Water absorption
Mild steel	508	4.8	4.5	25-350	245	0.23	NIL
Carbon-glass	396.5	2.6	8.6	99.5	323.4		0.07
Glass-sisal	224.7	1.41	6.4	110	13.62		0.12

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Table Pressure Vessel head comparison

Pressure vessel HEAD	Stress (maximumvalue)	Temperature ˚ C
Mild steel	2.580e^7pa	500 inner & outer transform
Carbon –glass laminates	2.69065e^7pa	500 inside uniform
Glass-sisal-laminates	2.692e^7pa	500 inside uniform

Table Pressure Vessel body comparison

Pressure vessel BODY	Stress (maximum value)	Temperature˚C
Mild steel	7.13e^7pa	500 inner & outer transform
Carbon –glass laminates	1.36e^9pa	500 inside uniform
Glass-sisal-laminates	7.1308e^7pa	500 inside uniform

CONCLUSION

- There is a percentage saving in material of 26.02% by using composite pressure vessels in the placemild steel based pressure vessel This decreases not only the overall weight of the component but also the cost of the material required to manufacture the pressure vessel. This is one of the main aspects of designer to keep the weight and cost as low as possible.
- This means that the stress distribution is uniform when compared to mild steel with composite pressure vessel. Minimization of stress concentration is another most important aspect of the designer. It also shows that the material is utilized most effectively in the fabrication of fibers.
- Theoretical calculated values by using different formulas are very close to that of the values obtained from ANSYS analysis. This indicates that ANSYS analysis is suitable for composite pressure vessels as compared to mild steel pressure vessel.
- While using a composite material it will reduce the environmental pollution.This can increase life of pressure vessel & reduce its cost. And also investigatenew techniques to reduce the stresses and use of higher strength materials and lower safety factors.

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