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MOYAHABO BRADLEY MOKETLA
Department of Mechanical Engineering Science, University of Johannesburg Johannesburg, South Africa, brmmoketla@gmail.com

MUKUL SHUKLA
Department of Mechanical Engineering Science, University of Johannesburg Johannesburg, South Africa, mshukla@uj.ac.za

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DESIGN AND FINITE ELEMENT ANALYSIS OF FRP LPG CYLINDER

MOYAHABO BRADLEY MOKETLA[1] & MUKUL SHUKLA[2]

Department of Mechanical Engineering Science, University of Johannesburg
Johannesburg, South Africa
Email: brmmoketla@gmail.com, mshukla@uj.ac.za,mukulshukla2k@gmail.com

Abstract— This paper entails the design and finite element analysis (FEA) of a LPG cylinder made of E-glass fiber, vinyl-ester resin and HDPE plastic composite The liner of the cylinder is made of HDPE plastic (blow moulding grade) and wound with continuous fiber E-glass composite with vinyl-ester polymer matrix. The cylinder cover is also made of HDPE plastic. The LPG cylinder was designed and tested for burst pressure of 3 MPa. The thickness of the cylinder was established to be 3.5 mm (1.5 mm of liner and 2 mm of FRP composite layer) using Abaqus software based FEA. Various design concepts were worked out alongwith a financial viability analysis. A strong, light, rust proof and semi-transparent LPG cylinder was aimed to be designed in this paper focusing on the use in the South African context.

Keywords*-Finite element analysis; design; LPG cylinder; standards;*

I. INTRODUCTION

Liquified petroleum gas (LPG) is a mixture of butane and propane gases stored under pressure, usually in steel cylinders. LPG is heavier than air, non-toxic and odourless. A smelling agent is added to aid users to detect leaks. LPG is a safe, economical and convenient fuel as it has high calorific value (13.8 kWh/kg, which is equivalent to 13.8 units of electricity), provides instantaneous heat, is easy to ignite and clean-burning and is very portable. It is the most environment friendly of the commonly used fossil fuels because it emits low levels of harmful combustion products. Approximately 280 million kilograms of LPG is consumed annually in South Africa. Typical uses of LPG include: cooking, space and water heating, refrigeration, lighting, brazing, soldering, welding, in school/technical laboratories, domestic households, restaurants, hospitals, small businesses, and recreation/leisure [1].

LPG appliances include: stoves/ovens, grills/braais, heaters (portable and fixed), instantaneous water heaters, lamps (portable and fixed), refrigeration and welding plant, and Bunsen burners. Appliances are designed to operate both at an unregulated high pressure (e.g. CADAC (or similar) type of camping appliances) and at a lower pressure controlled by a regulator mounted on the gas storage cylinder. High pressure and low-pressure appliances are not interchangeable. Most households use gas appliances with a small dedicated gas cylinder, rather than a reticulated system of gas piping and fixed storage cylinders. LPG storage cylinders are supplied in a range of standard sizes in two categories: camping/hobby type and household/industrial type. The larger (9-48 kg) cylinders are designed to operate at 7 bars and are tested at 30 bars [1]. SABS 087:1975, Part 1, code of practice for consumer LPG cylinder installation, is applicable to the storage of cylinders and gas piping in all cases when more than one cylinder, or a cylinder greater than 19 kg, is used on household premises. The most important installation consideration is the provision of good ventilation, preferably natural ventilation, in the storage and appliance area.

Three common fiber configurations are: continuous fibers, discrete (chopped) fibers and the woven fabric configuration, which is usually layered with polymer matrix to form a laminate. Optimal strength is achieved by the aligned, continuous fiber reinforcement, but the strength is highly anisotropic.

The design with composite materials is mostly centred on joints. The joints connect laminate sections together; provide mechanisms for the inclusion of secondary structures, such as fittings, ribs, bosses, and dividers; and connect the composites to surrounding structures; metals, wood, ceramics, plastics or other composites [2]. Typically, there are two basic joining methods, mechanical and adhesive (more popular). These are generally used independently in each joint, but can be combined to achieve special benefits. The choice of which adhesive is best is usually dictated by the type of composite to be bonded, the application of bonded composite, the service environment (temperature, solvent and moisture resistance, UV-light exposure, expected service life, and the subjected loading) and cost. The general classes of adhesives are: structural, hot melt, pressure sensitive, water-based, and radiation cured. In general, the structural adhesives dominate when joining of composites is required [3]. The most common polymers in the structural adhesives class are: epoxies, polyurethanes, acrylics, anaerobic, silicones and phenolics.

II. MOTIVATION AND PROBLEM STATEMENT

The product design specification (PDS) is a very important document in the design process as it contains all the information necessary for a design team to successfully produce a solution to the design problem. A PDS splits the problem up into smaller categories to make it easier for problem solution.

The perceived customer needs include -

- *Fuel level window*
  The existing steel cylinders have no accurate way of showing the rate of fuel consumption and level of fullness or emptiness of the fuel.
- *Weight*
  The steel cylinders are generally heavy to carry with hands for walking some unkown distance or to the refill stations.
- *Wheels and Retractable Handle*
  The LPG cylinders should be made to have a retractable handle and wheels for dragging option just as in a luggage trolley bag.
- *Rustiness*
  Most of the LPG cylinders are used in the kitchens, picnics, campings and grill-runners and may be placed outside the houses on the ground which is likely to have dust. The dust particles and rain water / moisture gain access to the cylinder and eventually the cylinder rusts.

Based on a conducted research, the propane cylinder in barbeque grill market, it was evident that the existing steel LPG cylinders were heavy for easy handling and lack an accurate way of showing remaining level of the fuel. For most consumers, the variation between the cylinder’s full and empty weight is the sole indication of how full the cylinder is at any given time. To avoid running out of propane during a cookout or like is one of the aims of the design of this semi-transparent type LPG cylinder. The composite LPG cylinders should be operating against equivalent models (Fig. 1) which include the following companies: The Supreme Industries Ltd. – India, Ragasco – Norway, Xinyang Cylinder - China, etc.

Figure 1. Photographs of steel, aluminium and FRP LPG cylinders.

Mission Statement	
Product	Store Liquid Petroleum Gas
Description	
Key Business or Humanitarian Goals	LPG business
Primary Market	Focus on LPG users
Secondary Market	LPG transporters Business executive
Assumptions	Minimum-1 l and maximum 50 l Long life (15-25 years)
Stakeholders	Corporations; wholesalers; retailers; users
Avenues for Creative Design	Ergonomic shape; store/capture LPG; Ease of dispensing
Scope / Limitations	Materials: Composite processing and mouldable plastics

III. DESIGN METHODOLOGY AND CONSIDERATIONS

Various design concepts were worked out and the concept shown in Fig. 2 (alongwith all the main components) was finally chosen after conducting a SWOT analysis.

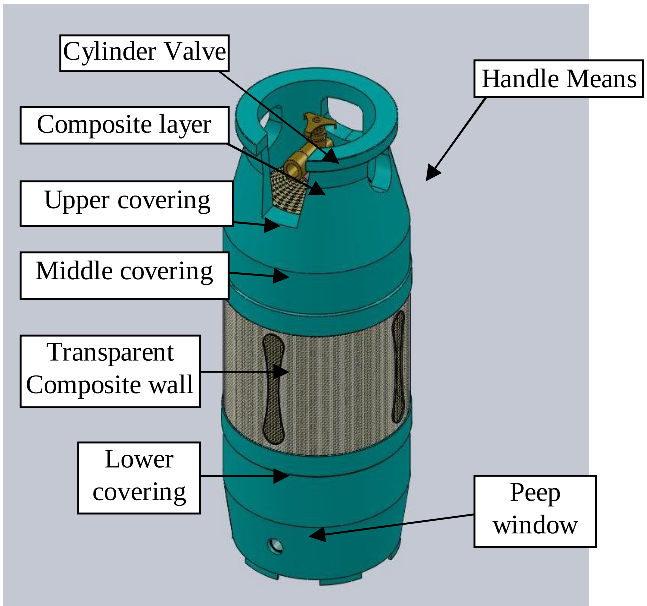

Figure 2. Main components of the finalized FRP LPG cylinder concept.

The composite LPG cylinders will comprise of three layers; the seamless polymer liner for gas containment to act as a gas barrier, the fiber structure to hold the burst pressure under extreme conditions and the fully integrated outer casing to help protect the valve/regulator and the pressure vessel from the surrounding environment.

The different components for the chosen concept were assigned the following materials:

- *Inner-layer/liner* = Plastic; type HDPE-Blow Mouldable Grade.
- *Outer-Liner* = E- Glass fiber; Strands/ filaments.
- *Coverings (Upper, Middle and Lower)* = Plastics; type HDPE-Injection Mouldable Grade.
- *Valve-Coupling* = Three types of material namely; HDPE-Injection Mouldable Grade (Coupling-Case), Brass (Coupling-Insert) and Copper (Coupling- Ring)

Figure 3 shows a blown up view of the various components of the proposed design. The *outer-layer* will be wound around the *inner-layer* as strands of filaments mixed with vinyl-ester resin. Vinyl-ester resin is ideally suited for being semi-transparent and having the ability to prevent UV rays.

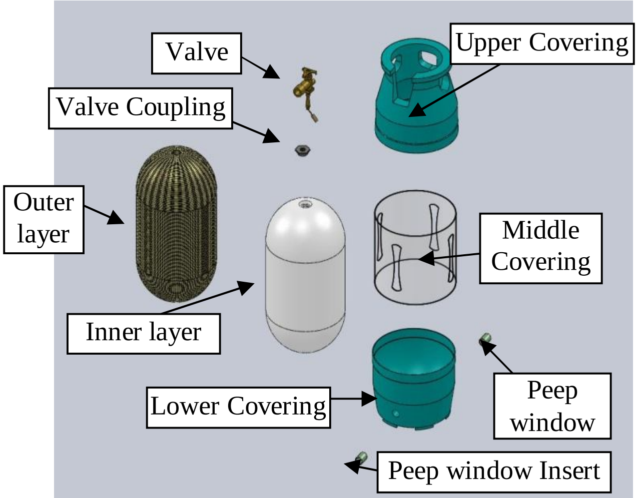

Figure 3. Exploed view of the designed FRP LPG cylinder.

The following manufacturing process is proposed for the different components:

- HDPE liner will be blow moulded.
- Fiber glass layer will be filament wound and oven cured.
- Test process pneumatic pressure test (3 MPa) and tightness test (1.8 MPa with helium).
- HDPE casing will be injection moulded and mechanically joined.

The relevant standards to be adhered to include [4,5]:

- SANS 10019:2008
- SANS 1825
- EN 12245
- ISO 11119-3

All containers shall be designed and manufactured in accordance with the requirements of the Pressure Equipment regulations (PER) of the occupational health and safety act, 1993 (Act No. 85 of 1993), in conjunction with the appropriate of the standards listed below:

- Fully Wrapped Composite Cylinders up to 450 L: EN 12245 (these containers shall have a lining as described in EN 12245 when manufactured for use in South Africa.)
- Fully Wrapped Fibre-Reinforced Composite Gas Cylinder with non-load sharing metal liners or non-metallic liners: ISO 11119-3.

The requirements for certificate of manufacture shall be as specified in the appropriate manufacturing standards (i.e. SANS 10019 & EN 12257).

All LPG cylinders are portable gas containers and can be regarded as pressure vessels. In any pressure vessel, the contents can be regarded as subject to change in phase frequently or oftenly (from liquid to gas or vice versa). LPG gas is heavier than air, and it can cause pockets of oxygen-depleted atmosphere in low-lying areas. However, it has been proven scientifically that LPG does not pose an ecological hazard, unless the gas/air mixture is ignited.

IV. FINITE ELEMENT MODELING AND ANALYSIS

The properties of E-glass fiber and vinyl-ester resin used for the estimation of composite properties are given in Table 1.

TABLE I. PROPERTIES OF E-GLASS FIBRE AND VINYL-ESTER POLYMER.

Properties	E-Glass continuous fiber	Cured Vinyl Ester
E (Elastic modulus)	72 GPa	3.4 GPa
G (Shear modulus)	29.51 GPa	1.25 GPa
σ (Tensile strength)	345 MPa	338 MPa
ρ (Density)	2580 kg/cm^3	1120 kg/cm^3
V(volume fraction)	60%	40%

The advantages of E-Glass Fibre include -

- Stiffness
- Less Weight
- Fatigue and Corrosion resistance
- Geometric flexibility
- Translucency

Yield Strength = 48.3 MPa of E-glass fiber. Based on Rule of Mixtures (RoM) concept the worked-out properties of E-glass/vinyl-ester composite are given in Table 2.

TABLE II. PROPERTIES OF E-GLASS FIBRE/VINYL-ESTER COMPOSITES.

Properties	Values	Units
E_1	44.56	GPa
E_2	9.54	GPa
G_{12}=G_{13}	5.86	GPa
G_{23}	5.99	GPa
Longitudinal-Transverse Tensile strength $\sigma_{12}= \sigma_{13}$	158.4	MPa
Transverse Tensile strength	162.1	MPa

σ_{23}		
Shear strength τ	79.2	MPa
$\nu_{12}=\nu_{21}$	0.28	

The entire CAD modeling and FEA simulation were carried out using the commercial FEA software Abaqus [6]. Composite laminate of thickness = 2mm was modeled using 10 plies in the Composite Layup module of Abaqus keeping the orientation alternately at 45°/-45° for each layer. The Engineering Constants option was invoked for assignment of composite material properties. Burst Pressure is the designated pressure acting on the Inner Layer/Liner as per the design standards (EN12245:2002) for testing the prototypes of the composite LPG cylinder [4]. The value assigned to the burst pressure = 3 MPa (30 bar) and is applied as a uniform pressure load. 3-d linear hexahedral (brick) elements (total number 780) were chosen for the FEA meshing. Attempts were also made to use the third party addon module of Filament Winding within Abaqus. The same where unsuccessful owing to version compatibility issues.

Fig. 4 shows the Von-mises stress contour plot of the composite LPG cylinder after Static FEM analysis.

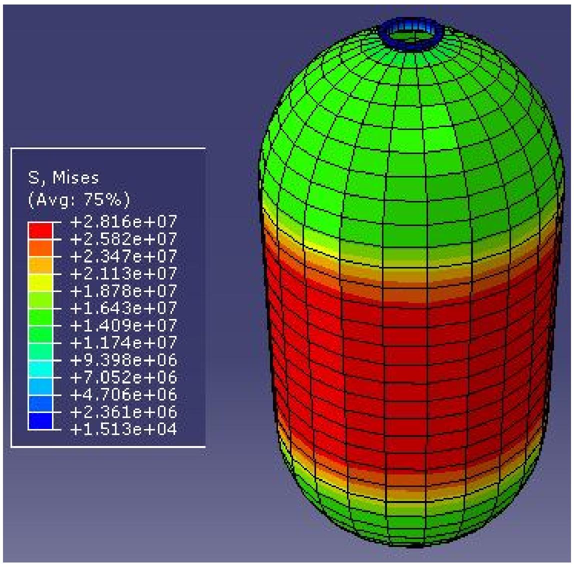

Figure 4. Von-mises stress contour plot.

The results show no signs of immediate failure. The maximum operating LPG-cylinder pressure is less than 13 bars and the testing was done at 30 bars in the present study. Hence, a factor of safety in the range of 2.15-9.1 was established. When product failure could result in serious injury or loss of life, exhaustive testing and higher safety factors have to be employed.

V. CONCLUSIONS

Three design concepts were generated and the best concept was finally selected using a multi-criteria comprising of functionality, ergonomics, convenience, ease of manufacturing, cost etc. satisfying the customer and design needs. The FEA results showed that the material being used; HDPE-Liner of 1.5 mm thickness and the wrapping composite layer of 2 mm thickness are suitable for the product to behave safe. The results show that the maximum burst pressure the chosen thicknesses could sustain is about 28 MPa which is well above the subjected pressures. With the introduction of composite cylinders, dust and rain water will become a smaller concern. The FRP LPG cylinder is believed to be superior to the existing steel and aluminium cylinders in terms of weight, cost, ergonomics (semi-transparent cylinder wall), safety, environmental compatibility and user friendliness. Further, studies on design analysis, optimization and fabrication of a test prototype are in progress.

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