Available online at
www.ijacskros.com

Indian
Journal of Advances in
Chemical Science

Indian Journal of Advances in Chemical Science 3 (2014) 33-37

Development of Composite Cylinders for Aerospace Applications

R. Indu Shekar[1]*, T.M. Kotresh[1], T.S. Raghu[1], B. Vijay Krishna[2]

[1]Protective Equipment Technology, Defense Bio-Engineering & Electro Medical Laboratory, Bengaluru - 560 075, Karnataka, India. [2]CNC Technics Pvt Ltd, Kukatpally, Hyderabad -500 072, Andhra Pradesh, India.

Received 8th October2014; Revised 10th November 2014; Accepted 25th November 2014

ABSTRACT

High-performance composites are increasingly becoming an essential part of aircraft structural composites and are being explored for space and underwater applications. The concept of hybrid yarn systems, co-weaving and co-mingling, has further enlarged the scope of thermoplastic composites that have demonstrated potential performance advantages over conventional thermoset composites. To design high pressure composite cylinders with the highest possible safety, reliability and minimum weight considerations, the behavior of composite structures under various mechanical and thermal loadings need to be well understood. The fibers, trajectory of the fiber path and the corresponding fiber angles that are used in commercial cylinders cannot be chosen arbitrarily for the high pressure cylinders and require a different design approach to meet stringent requirements of EN or DoT specifications. Defense biod-engineering and electromedical laboratory has initiated work in this direction to develop and indigenize high-pressure composite cylinders for various lifesaving equipment's and finally achieve self-reliance in the above field. This paper describes system design and system engineering considerations for the Type-3 and/Type-4 high-pressure composite cylinders required for aerospace applications. Type-4 composite cylinders offer great promise in the near future for advanced composites and space applications.

Key words: *Aramids, Carbon, Hybrid composites, Plastic liner.*

1. INTRODUCTION

Thermoset based composites using epoxy resin systems currently dominate the composite industry. Glass-reinforced epoxy composites are extensively used in the structural composites of the aircraft industry due to low shrinkage, ease of fabrication, chemical resistance, and higher mechanical and electrical properties. The above characteristics coupled with techno-economic considerations are mainly responsible for their extensive use in aerospace, automobile and marine engineering applications. However, the advent of high-performance fibers (carbon, aramids) has enhanced the scope of advanced structural composites as the above composites outperform the conventional glass-epoxy composites due to their superior mechanical properties. In recent years, more research work is being directed toward exploring the potential advantages of high-performance fibers using hybrid concept. There have been a number of approaches followed by archers to achieve high-performance structural composites. In recent years, fabrication of high-performance composites using engineering materials particularly poly ether ether ketone (PEEK) as a thermoplastic fiber matrix has received considerable attention for aerospace applications. The semi-crystalline nature of PEEK can be effectively used wherein strain to failure ratio, ductility are important. Thermoplastic composites with PEEK in reinforced form, powder and film has been tried out by researchers and a significant amount of data is available related to PEEK degradation, crystallization kinetics and mechanical properties [1-10]. Although work related to development of carbon-PEEK composites utilizing unidirectional hybrid yarn fabrics is well documented [11-14], comprehensive study on the development of fiber-fiber based hybrid composites using engineered resin system for high temperature aerospace applications is still scanty. The use of hybrid fiber systems will also address some of the important aspects related to drapability, strain to failure ratio while fabricating critical and irregular shaped components and provide conformability to highly complex contours. Hybrid fabric based composites encompassing different high-performance fiber systems are expected to offer better resistance to damage than the composites made out of single fiber in both warp and weft direction. Hybrid yarn systems with two or more fiber materials combined using comingling or co-weaving technique is the latest approach used both in advanced composites and in applications where filament winding is primarily used

*Corresponding Author:
E-mail: rindushekar@gmail.com

as a means of manufacturing composite structures. Typical examples of hybrid thermoplastic composites for aerospace applications include carbon-PEEK, carbon-polyphenylene sulfide and aramid-PEEK which are used to combine the benefits of each fiber into a single composite product. The above new approach of fiber-fiber composites have demonstrated potential performance advantages over conventional thermoset-matrix composites with added advantage of low cost manufacture, quick process cycle, enhanced damage tolerance, better impact properties and adaptability to undergo minor structural changes when subjected to high temperature treatments. Another area that is gaining significant attention among the research community is the fiber reinforced nano-composites, based on aramids using carbon nanotubes (CNT) and nano-clay. Although applications of nano-materials is widely explored in the field of composites, most of the work is focused in the area of conductive carbon composites, CNT reinforced composites for electrical application, radomes used in unmanned-air-vehicles and nano-clay filled epoxy matrix [15]. By having materials at the nanometer scale the resulting composite material can be engineered to achieve some specific properties (matrix modification, gas impermeability), which are expected to enhance the performance of the final product better than the ones at those achieved at the micro scale. However, processing of composites poses technical difficulties with some of the properties especially Impact strength and toughness undergoing drastic decrease.

Composite high-pressure cylinders are required in many aerospace applications such as gas fuel equipment, portable oxygen storage systems for life-saving equipment's, rocket motor cases and inflatable systems. The liners of Type-4 cylinders are primarily used as non-load sharing type permeation barriers (contributes not more than 5-10% of the ultimate burst pressure) and hence do not provide structural strength. By virtue of its low modulus, plastic liners although not considered as a structural component of a design system still contributes in effectively transferring the load to the primary load bearing composites. They are increasing being used, and further explored for NASA missions and military aircraft which require a high propulsion capability as well as light weight systems. Since the fuel tank is one of the items with the largest mass in air vehicles as well as space craft, reducing the weight while keeping the large capacity of the fuel ensures longer mission cycles and sorties and also better efficiency in applications involving propulsion systems. The load sharing liner made of metallic material (Type-3) is used in rescue systems of underwater applications. Composite pressure vessel with the latest technology encompassing non-load sharing liner (Type-4) is reported by few authors [15-19]. These type of plastic or fiberglass reinforced plastics liners are manufactured by blow extrusion or rotomoulding and hybrid fabric composites.

In our ongoing efforts to develop an advanced hybrid composite and subsequently a high pressure composite cylinder, an effort has been made in the present work to investigate the following; (i) development of high pressure composite cylinder based on hybrid composites; (ii) development of glass and aramid fiber based hybrid composites (thermoset epoxy based) for aerospace applications.

2. EXPERIMENTAL

2.1. Materials and Methods

2.1.1. E-glass, carbon (T300) and twaron (2200)

E-glass, carbon (T300) and twaron (2200) were obtained from Toray and Teijin respectively. The liquid epoxy resin LY 556, with a viscosity of 10,000-12,000 cps at 25°C and specific gravity 1.15-1.20 at 25°C and amine based hardener (HY 951) were from Huntsman.

2.1.2. Manufacture of filament wound composite cylinders

The liners were wound on 5-axis filament winding machine. R-glass (800 tex), carbon (12 K) and twaron (245 tex) filaments were used in the filament winding. The resin and hardener used in the filament winding process and curing conditions were same as that used in the preparation of thermoset based hybrid composites.

2.1.3. Techniques

Filament winding of the composite cylinders was carried out on 5-axis machine. Aluminum liner (AL) 6061 liner was used for Type-3 cylinder and high density polyethylene and nylon liner for Type-4 cylinders. Burst pressure and volumetric expansion studies of the composite cylinders were carried out as per BSEN 1975:2000.

3. RESULTS AND DISCUSSION

3.1. High Pressure Composite Cylinders (Type-4)

3.1.1. Methodology for adapting ply sequence and filament winding considerations

Resin impregnated continuous reinforcement fibers were wound on the liner on a computer-aided design winding computer numerical control Type-5 axis horizontal bed filament winding machine. The resin-fiber ratio and a variable winding tension were maintained to get uniformity in the strength and optimum realization of filament strength and uniform resin ratio. Initially, the tension on the first leveler hoop winding was maintained between 2 lbs and 3 lbs. The tension (5-6 lb) was increased for subsequent three windings to prevent any possible buckling. Precise and controlled tension was maintained by specially adapted electronic tensioners. Resin impregnated filaments are wound over the liner in Hoop axis pattern, which is of 0.3-0.5 mm thickness (1 layer). After hoop winding, polar (helical) winding pattern was used wherein bands of filaments were wound over the liner in the axial direction to obtain the desired thickness. The process was continued till the required number of windings was carried out to obtain desired thickness. Additionally a small heating unit consisting of heated rollers was used to pass the reinforcement materials (twaron) to remove the moisture present in the material. However, both glass and carbon fibers being hydrophobic in nature the above heating arrangement was dispensed with. The advantage with plastic liners is that they do not yield unlike AL wherein the material yields in the plastic region each time it is subjected to load, and this particular characteristic influences the cyclic life (typically the composite cylinders are subjected to 10,000 cycles of repeated pressure cycles before being considered for a known service life usage). The hoop components are not sufficient to cover the entire reinforcement requirement. This coupled with the fact that hoop stress is twice that of the longitudinal stress for a composite cylinder calls for the application of additional windings. Further higher helical thicknesses near the pole openings take care of the hoop stresses, the helical thicknesses at the dome near the junction are sometimes inadequate to provide sufficient cover to the hoop stresses. Accordingly, additional layers (doily) of high strength fabric are laid-up interspersing the helical layers from around the cylinder-to-dome transition to the inflection point at each dome. The angle of winding at various points on the end domes (geodesic path) are obtained by using the well-known Clairut theorem sin Φ=constant, Φ is the winding angle between a filament and a meridian line in a point on the surface and "r" is the radius at different station, where the cylinder radius is the maximum radius and pole radius is the minimum radius. (preliminary design was performed using netting analysis methods to address the inner pressure loading). Netting analysis assumes that the fibers provide all of the stiffness and strength in the cylinder. This assumption provides an excellent basis for quick calculation of composite thickness [16]. To prevent the failure in the dome or by boss blowout, the cylinders were designed with 0.6-0.8 stress ratio. Different plies were arranged to maintain symmetry of the plies with respect to the mid plane as balanced symmetry is a better option for the axi-symmetric structures. This is because the loading in a particular plane does not cause deformations in other planes. The number of helical plies and hoop plies are calculated based on following equations [19].

$$t_{F\alpha} = \frac{PR}{2\sigma F\alpha \cos 2\alpha} \quad (1)$$

$$t_{F}\infty = \frac{PR}{2\sigma F\infty}\left(2 - \tan^{2}\alpha\right) \quad (2)$$

where t; thickness; P, pressure; R, radius, Fα, operating stresses in helical fibers and $t_F\infty$ operating stresses in hoop fibers; α, helical angle and ∞, hoop angle.

Ideally, the best practice is to lay the hoop layers as the outer layers in order to give consolidation effect on the helical layers. Helical failures are strongly affected by the bending loads which arise due to the discontinuities at the tangent line and at the polar boss regions. Hence, design stresses for the helical fibers are almost always selected lower than hoop fiber allowable. For designing the pressure cylinder wall thickness, the ultimate tensile strength of the R-glass epoxy composite was taken as 1200 MPa at 60% fibers and 40% resin combination which was tested by NOL ring test method.

Table 1: Burst strength test results of composite pressure cylinders.

Parameters	R-GC	R-GT	100% C	100% C
Hardener	Fine hard 972	Fine hard 972	Fine hard 972	Fine hard 972
Resin	Epoxy 556	Epoxy 556	Epoxy 556	Epoxy 556
Tex	R-glass 800	R-glass 800	-	-
	Carbon 12 K	Twaron 245	Carbon 12 K	Carbon 12 K
Weight of the liner, g	540 (AL)	540 (AL)	240 (HDPE)	488 (nylon)
Weight of the cylinder, g	910	940	700	950
Total thickness of composite, mm	3.6	5.0	5.5	5.5
Leakage at 300 bar after holding it for 1 min	Nil	Nil	Nil	Nil
Test pressure of composite cylinder, Bar	305	300	300	300
	No leakage	No leakage	No leakage	No leakage
Burst pressure, bar	>810	343-500	>700	>700
Volumetric expansion, ml at 300 bar	<6%	<6%	-	-
Pressure cyclic test, cycles	-	-	-	>16000

AL: Aluminum liner, R-GC: R glass-carbon, R-GT: R glass-twaron, C: Carbon

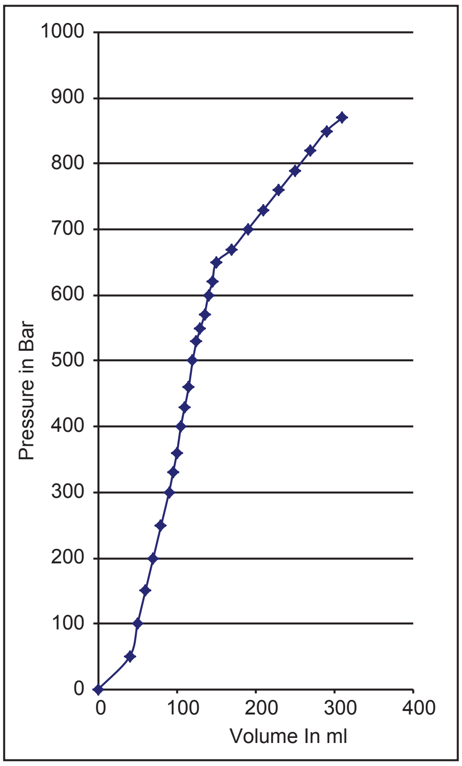

Figure 1: Burst pressure and volumetric expansion results of cylinder.

Pressure kg/cm^2	Volume ml
0	0
50	40
100	50
150	60
200	70
250	80
300	90
330	95
360	100
400	105
430	110
460	115
500	120
530	125
570	135
600	140
650	150
700	190
730	210
760	230
790	250
850	290
870	310

The nylon liner material used in Type-4 cylinder has a temperature limitation (continuous use temperature of not more than 140°C). In the present application intended for oxygen bottles, the temperature is not expected to go beyond 70°C during repeated pressure cycles. The maximum expected operating pressure of the composite pressure cylinder (1 L capacity) is 200 bar. The burst pressure results of AL liner and plastic liner based composite cylinders are shown in Table 1 and Figure 1. From Table 1, it can be seen that the composite cylinders based on R-glass-carbon and 100% carbon filaments were found to exhibit satisfactory results without any leakage and meeting the functional requirements in terms of proof (300 bar) and burst pressure (600 bar). The glass-twaron based cylinders although passed leakage and proof pressure but failed to meet the requirement of burst pressure that is 3 times the operating pressure. The possible reason for the above failure may be attributed to the compatibility between aramid (twaron) and epoxy which is found to be poor compared to glass-epoxy. Amino silane coupling agent which is very effective on glass is mainly responsible for good interlaminar shear strength, whereas the spin finish, given on aramid (twaron) is not so effective to achieve good impregnation of epoxy. This was witnessed in the post analysis of aramid based composite cylinders subjected to burst pressure. Aramid based cylinders failed to cross beyond 500 bar burst pressure, whereas the carbon based cylinders (both AL as well as plastic liner based cylinders did not fail even up to 700 bar). The volumetric expansion of the cylinder was found to be well within 5%, which fulfills the EN requirements.

4. CONCLUSIONS

High-pressure composite cylinders have been designed for maximum operating pressures of 200 bar. The carbon fiber based composite cylinders Type-3 (AL liner) and Type-4 (plastic liner based) with burst pressure of more than 700 bar exhibited very low volumetric expansion met the primary functional requirements with a safety of margin of more than 3. The Type-4 composite cylinders offer great advantages as it eliminates the laborious process of manufacturing AL liner, complicated interface mechanism between metal and textiles and significant weight savings which can be used to advantage in space applications to enhance the payload capacity and endurance missions.

5. ACKNOWLEDGMENTS

The authors would like to thank Director, Defense Biod-Engineering and Electromedical Laborator and Dr. T.M. Kotresh, Joint Director, for extending the necessary support in carrying out the work and preparing the paper.

6. REFERENCES

1. K. Friedrich, (1998) Commingled yarns and their use in composites. In J. Karger-Kocisis, (Ed.),

Polypropylene: An A-Z Reference, London: Chapman and Hall.

2. J. Karger-Kocsis, (1996) Composites. In J. C. Salamone, (Ed.), ***Encylclopedia of Polymeric Materials,*** Boca Raton, FL: CRC Press, p1378-1383.
3. T. Matusuo, N. Ikegawa, (1992) Impregnation behaviour and longitudinal bending properties of thermoplastic composites made from commingled twisted spun yarn. ***Advanced Composites Letters,*** **1:** 116-118.
4. T. Vu-Khanh, J. Denault, (1991) Processing-structure-property relations in PEEK/Carbon composites made from commingled fabric and prepreg, ***Journal of Thermoplastic Composite Materials,*** **4:** 363-346.
5. G. O. Shonaike, H. Hamada, Z. Maekawa, M. Matsuda, T. Yuba, T. Matsuo, (1996) The influence of cooling conditions on the mechanical properties of commingled yarn composites, ***Journal of Thermoplastic Composite Materials,*** **9:** 76-89.
6. S. Ramakrishna, D. Hull, (1994) Tensile behaviour of knitted carbon -fibre-fabric/epoxy laminates-Part I: Experimental**,** ***Composites Science and Technology,*** **50:** 237-247.
7. R. Indu Shekar, T. M. Kotresh, M. S. Subbulakshmi, S. N. Vijaya Lakshmi, A. S. K. Prasad, V. C. Padaki, P. M. Damodhara Rao, (2007) Development of Hybrid Composites for Aerospace Applications International Conference on FRP, 9-12 Sept., Port Elizabeth, CSIR, South Africa.
8. D. Alagirusamy, R. Fangueiro, R. Portugal, V. Ogale, N. Padaki, (2006) Hybrid yarns and textile performing for thermoplastic composites, ***Text Prog,*** **38(4):** 1-71.
9. Kay, D. & Trg, E. Boston., (1965) PEEK degradation, crystallization kinetics and mechanical properties, ***IEEE Trans,*** **13:** 188.
10. M. Sumerb, H. Unala, A. Mimaroglub, (2008) Evaluation of tribological behaviour of PEEK and glass fibre reinforced PEEK composite under dry sliding and water lubricated conditions, ***Wear,*** **265:** 1061-1065.
11. C. Thanomsilp, P. J. Hogg, (2005) Interlaminar fracture toughness of hybrid composites based on commingled yarn fabrics, ***Journal of Computer Science and Technology,*** **65(10):** 1547-1563.
12. M. D. Wakeman, L. Zingraff, P. E. Bourban, J. A. E. Månson, P. Blanchard, (2006) Stamp forming of carbon fibre/PA12 composites – A comparison of a reactive impregnation process and a commingled yarn system, ***Journal of Computer Science and Technology,*** **66(1):** 19-35.
13. N. Bernet, V. Michaud, P. E. Bourban, J. A. E. Månson, (2001) Commingled yarn composites for rapid processing of complex shapes, **Composites Part A: Applied Science and Manufacturing, 32(11):** 1613-1626.
14. L. Zhang, M. Miao, (2010) Commingled natural fibre/polypropylene wrap spun yarns for structured thermoplastic composites, ***Journal of Computer Science and Technology,*** **70(1):** 130-135.
15. I. Kosar, (2008) Development of a liner-less composite CNG cylinder and improved mechanical properties of cylinder materials, Thesis, Hong Kong University of Science and Technology.
16. M. Madavi, K. V. J. Rao, K. Narayan Rao, (2009) Design and analysis of filament wound composite pressure vessel with integrated - end domes, ***Defense Science Journal,*** **59(1):** 73-81.
17. J. Hu, (2009) Modeling and simulation of high pressure composite cylinders for hydrogen storage, Ph. D Dissertation. Missouri University of Science and Technology.
18. R. P. Willardson, D. L. Gray, T. K. Delay, (2011) Improvements in FEA of composite overwrapped pressure vessels, Huntsville: NASA – Marshall Space Flight Center.
19. S. M. Lee, (1993) Filament winding. In: ***Handbook of composite Reinforcements,*** Weinheim: Wiley-VCH Publishers.

***Bibliographical Sketch**

Dr. R Indu Shekar obtained his M.Tech from Bangalore University in 1994 and PhD from VTU in 2011. Joined Defence Research and Development Organization (DRDO) in 1994 and is working in Defence bioengineering and electromedical laboratory, Bangalore, India. His research areas in the last 21 years include personal protective systems and clothing for high altitude conditions, flame retardant fabrics, and technical structures based on fabric engineering and heated textiles. His PhD work is on 'High temperature fiber–fiber composites for aerospace applications'. He has published more than 40 papers and has three patents in his field and presented papers in International forums.